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—OF—

AGRICULTURAL CHEMISTRY

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PRINCIPLES OF AGRICULTURAL CHEMISTRY

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Principles of Agricultural Chemistry

BY

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Preface.

In this book the author aims to present the fundamental principles of agricultural chemistry. The point of view is that of the chemist dealing with agricultural problems; the attempt is made to emphasize chemical methods of investigation, and inculcate scientific habits of thought. Details are omitted so far as they are not necessary to the proper treatment of the subject. Practical applications, which are necessarily local, are left out as much as possible. The book thus treats of agricultural chemistry rather than of chemical agriculture. It attempts to give a comprehensive view of the subject, and to prepare the student for a more detailed study of its various phases.

This book is based upon lectures given for a number of years to students in Agriculture at the Agricultural and Mechanical College of Texas. A number of references are given, some of which do not refer to the articles in which the facts were first published, but to articles of interest or of value to the student, which may contain numerous references to the literature of the subject. It was not deemed desirable nor was it practical, to give references for all the statements made in the text.

The author is fully aware of the fact that there is room for differences of opinion as to what should be treated or omitted in a work of this character. He also realizes the difficulty of avoiding errors, and will be grateful to the reader who may bring errors to his attention, or offer suggestions for the improvement of the book.

Valuable assistance has been received from Mr. S. E. Asbury, Assistant State Chemist, and especially Dr. C. P. Fountain, Professor of English.

Agricultural and Mechanical
College of Texas,
College Station.

Aug. 30, 1912.

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DEPARTMENT
—OF—
AGRICULTURAL CHEMISTRY
THE PENNSYLVANIA STATE COLLEGE

Principles of Agricultural Chemistry

CHAPTER I.

INTRODUCTION.

The object of agriculture is the profitable production of useful plants and animals. Agriculture is therefore an art and not a science, since an art relates to something to be done, a science to something to be known. We may, however, speak of the science of agriculture, meaning the body of organized knowledge appertaining to this art.

Success in agriculture depends upon ability to manage men and things, to take advantage of markets and local conditions, as well as upon a knowledge of how to produce plants and animals, and also upon skill in transforming this knowledge into practice. That is to say, practical agriculture is a business and business methods must be followed in order to succeed in it.

More than any other pursuit, agriculture is underlaid by a body of complex scientific principles, many of which are applied, knowingly or unknowingly, by the practical farmer.

Agricultural Experiment Stations.—The importance of agriculture has been recognized by civilized governments in the establishment of agricultural experiment stations and agricultural colleges. The oldest, and the most renowned experiment station, that at Rothamsted, England, is not a State institution, but was established, conducted, and endowed by Sir John Lawes, the work having been begun on a small scale in 1828. Nearly all of the experiment stations have been established since 1870; most of those in this country date from 1876 to 1882. In addition to conducting a great variety of experiments along agricultural lines, these stations make analyses of soils, fertilizers, feeding stuffs, etc. There is at least one experiment station in each State of the United States and, in addition, the United States Department of Agriculture (U. S. D. A.); these agencies are doing a great deal of work for the advancement of agriculture. While our knowl-

edge of the principles of agriculture is largely due to the work of the experiment stations, it is chiefly due, let it be said, to the work of *chemists*.

Agricultural Chemistry.—Agricultural chemistry is the application of chemistry and chemical methods of investigation to agricultural problems. It deals, on the one hand, with fundamental causes of phenomena, and, on the other, with practical applications to agricultural practice. The chemist was the first of the scientists to turn his attention to agriculture, and his results were so fundamental, and practically important, and the science of chemistry was capable of such broad application to agriculture, that for a long time the great body of scientific knowledge regarding agriculture was known as agricultural chemistry. The chemist has not hesitated to avail himself of the sciences of geology, mineralogy, physics, botany, or such other sciences as were needed in the solution of the problems at hand. Many of the problems of agriculture are complex, and their solution requires the harmonious coöperation of several sciences. Take, for example, the transformation of organic nitrogen to nitrates, a very important process in the soil. This is a chemical change, accomplished by means of micro-organisms, and both chemistry and biology are necessary to give a complete explanation of this phenomenon, though the explanation has been largely worked out by the chemist.

Scope of the Subject.—In a wide sense, agricultural chemistry signifies the study of all the scientific laws involved in plant and animal growth, whatever the several sciences which may be involved. We may look at this subject as a fabric in which chemistry is so interwoven in warp and woof that, if removed, the pattern would be destroyed; if the other sciences were removed, the pattern would be very imperfect.

It shall be our object to deal with the principles ascertained in the application of chemistry to agriculture, taking up the subject from the view-point of the chemist. In particular we shall attempt to indicate the methods which have been followed in securing important results. Agricultural science is founded upon

and grows by experiments. An experiment is a question put to nature. It matters not what theories or lack of theories are behind the experiment, if the question is carefully and skilfully put, and if we see with a clear eye, not dazed by prejudgment, the answer will advance our knowledge. The knowledge of how experiments have been planned helps us to plan them for ourselves; the knowledge of how a certain problem has been solved keeps us from regarding the knowledge so secured as dogmatic, and gives us an opportunity to test it for ourselves if we so desire. The scientific investigator cannot accept the conclusions of others at their face value; he must examine the evidence offered, and satisfy himself that the evidence justifies the conclusion.

Division of the Subject.—Agriculture falls naturally into two divisions—the production of plants, and the production of animals. Usually in the case of plants, only a portion of the plant is desired, such as the grain ot wheat or corn, the tubers of potatoes, etc. The remainder is considered as a by-product and such disposition is made of it as appears feasible. The disposition of the by-product has considerable effect upon the fertility of the soil, or the profits of agriculture. In some cases, as in the preparation of hay, the entire plant is utilized. In other cases, by-products result in the preparation required before the product can be placed on the market, such as threshing of wheat or rice, husking or shelling of corn, etc.

The study of plant production involves a study of the conditions which are favorable to plant life, the composition and properties of the atmosphere and the soil, the maintenance of soil fertility, fertilizers, methods of soil treatment, etc., as well as the composition and properties of the plant products, and a study of such chemical changes as are involved in their production or preparation for market.

The study of animal production involves a study of the principles of animal growth and nutrition, the composition and properties of feeding stuffs, their preparation or preservation, and the methods of feeding for different purposes, such as meat, milk, wool, etc.

We will begin the study of agricultural chemistry with a study of the chemical laws governing the production of plants. We must study the conditions best suited to the growth of plants; ascertain how these conditions are filled by the air and soil in which they grow; learn how to overcome unfavorable conditions in the soil, and how to maintain and increase its productiveness. In addition, we must study the composition of the plant.

Agriculture Primarily the Production of Organic Matter.—Agriculture deals primarily with the production of organic matter. Organic matter, for the purpose of the agriculturalist, may be defined as the compounds of carbon which possess chemical energy. In agriculture, inorganic compounds of carbon and other bodies are caused to combine with the energy of the sun, so as to produce organic compounds containing energy, which may supply heat or energy for the use of man or other animals, which may serve as fuel, or be used for other purposes. The primary object of agriculture is thus to store up the energy of the sun. The production of organic matter is accomplished by means of plants.

Products of Plant Life.—The various soil and atmospheric agencies, acting upon the life within the seed, produce a plant built up by sunshine, water, carbon dioxide from the air, and several mineral substances from the earth. The plant is composed mostly of complex organic substances, rich in carbon, and contains a comparatively small amount of material withdrawn from the soil. It is suitable for the food of animals, while the materials from which it is built are not. If dried and heated sufficiently, the plant burns and gives off heat.

It has been found that the heat which is secured in the burning of plants, or which can be utilized as heat or other forms of energy by animals which consume them, comes from the sun. The energy of the sun is used to decompose carbon dioxide, water, and nitrates, and to form complex organic compounds. These bodies then contain stores of energy which can be utilized by animals or in other ways. Plants thus store up the energy of the sun, and may also be regarded as media for furnishing animals

with the sun's energy. All energy utilized by plants or animals thus comes directly or indirectly from the sun.

We have used the term "organic" in connection with the compounds formed in plants. It was believed in the beginning of the 19th century that organic bodies, such as starch, sugar, urea, etc., differed greatly in chemical nature from inorganic bodies, and could only be formed under the influence of mysterious life-forces. But in 1820 Wöhler prepared a product of animal life found in the urine, called urea, from a purely inorganic body, ammonium cyanate. The supposed barrier between organic and inorganic substances was thus broken down; great numbers of organic compounds have since been prepared, some of which occur in nature, and the chemist now hardly places bounds to the possibilities of organic synthesis in the laboratory. It is well known that organic and inorganic bodies obey the same laws, though on account of the size and complexity of the subject, organic chemistry is still treated separately.

As far as agricultural chemistry is concerned, there is a wide difference between organic and inorganic bodies. Organic compounds may serve as food for animals, but inorganic do not. On the other hand, inorganic bodies serve as food for plants; but to only a very limited extent, if at all, do plants make use of organic bodies. With the aid of light, plants build up organic bodies which possess chemical energy, from inorganic bodies which do not possess chemical energy. For the student of agriculture, organic compounds are compounds of carbon which possess chemical energy, and they are usually the products of plants or animals.

Conditions of Plant Life.—The conditions necessary for the production of organic matter by green plants may be summed up briefly as follows:

(1) Light.
(2) Favorable Temperature.
(3) Water.
(4) Certain elements in certain forms of combination.

If any of these conditions are unfavorable, the plant will suffer

and perhaps die. The varying needs of different kinds of plants and their varying powers of satisfying these needs, permit plants to flourish in nature under a great diversity of conditions, as in the tropics, or in arctic regions, in shade or in sunshine, in water or in deserts. The conditions of temperature, light, or water favorable to cultivated plants are more limited than those of wild plants, but still the range is wide.

The simple conditions we have named are rendered more complex by the varying degree in which different classes of plants require them, and the varying powers they have of supplying their needs. The varying powers of soils to supply the needs of the plant growth thereon, and the necessity of maintaining the fertility of the soil, render the matter still more complex.

Relation of the Plant to the Atmosphere.—The atmosphere has its part in supplying some of the conditions for the growth of plants, the more important being light, heat, carbon dioxide, and, indirectly, water. The atmospheric conditions are less susceptible to control than soil conditions; nevertheless, sometimes a partial control is established, as temperature and humidity in green houses, light in the growth of plants by artificial light or under shade, and the prevention of frost by smoke clouds. The atmosphere indirectly supplies the plant with small quantities of combined nitrogen, through the soil.

Relation of the Plant to the Soil.—The relation of the plant to the soil is more complex than its relation to the atmosphere. The functions of the soil are primarily to support the plant, supply it with water and certain necessary elements, and maintain a favorable temperature. These are, however, fulfilled in a very complicated manner.

Methods of Experiment.—The methods of studying the problems of agricultural chemistry must be varied to suit the end in view. At various points we shall bring in experimental evidence in support of certain views, thus illustrating by example some of the more important methods. The earnest student is advised to study

the original papers that mark important steps in agricultural science.

The problems of agricultural chemistry are often so complex and interrelated as to render their solution very difficult. In the study of them, one should endeavor to vary one factor at a time and keep the others constant. Let us take, for example, the essential elements in plants. By chemical analysis we can ascertain that plants contain certain elements. Which of these are necessary to the plant and which are not? The solution of the problem is obtained by growing the plants under the most favorable conditions, with an ample supply of all the elements found in the plant except one. If the plant does well, then this one is not needed. If it does very poorly, and all the conditions are most favorable, then the element is necessary. The difficulties in following out this method of experiment will be presented later.

It is obvious that if two variables are present, it would be impossible to tell which one produced a given effect, or what part each had in it. The conditions of agricultural experimentation are sometimes such that it is difficult to reduce the experiment to a variation in one variable, and sometimes proper precautions are not taken to eliminate other variables. Take, for example, a field experiment on corn, or any other crop. Variables are weather, insects, seed, soil, etc. We attempt to eliminate them by subjecting the entire field to the same conditions, but it is very difficult to make all conditions uniform.

Agricultural investigations must be brought to the test of actual conditions. Conditions in the laboratory or in pot experiments, are often radically different from those which prevail in practice. The gap between the two must be bridged by experiment, rather than by theory.

Observation and Experience.—Agricultural knowledge is largely based upon observation and experience. General agricultural practice is based upon experience, passed on from one generation to another. Experience is, indeed, based upon experiments, though the experiments are not always consciously

made, very often imperfectly planned and often very expensive. Sometimes the trial is made intentionally, and sometimes the trials are more or less unintentional and due to ignorance. Usually the trials are very limited in scope, and therefore differ widely from consciously organized experiments dealing with definite problems.

CHAPTER II.

ESSENTIALS OF PLANT LIFE.

Prior to 1840, comparatively little was done to apply chemistry to the solution of agricultural problems. Much information was collected regarding the chemical composition of soils, plants, and animals, and a few books discussing the relation of chemistry to agriculture were published, those of Sir Humphrey Davy and Thaer being perhaps the most important, but the fundamental principles of plant and animal nutrition were not recognized, and the books offered little of practical importance to the farmer.

At that time the prevailing theory was that plants feed upon the organic matter, or humus, of the soil, just as animals feed on organic matter. According to this theory, the soil should be kept full of vegetable matter to feed the plant. The ash or mineral matter of the plant, whose presence was known and could not be ignored, was thought to act as a stimulant, and not as food. Indeed, Thaer, and perhaps others, held that mineral matter could be created by plants.

The great German chemist, Justus von Liebig, in 1840 published a little book entitled "Chemistry in its Application to Agriculture and Physiology," which developed an entirely new theory of plant nutrition. Plants, he said, do not secure their organic matter from the soil, but from the air. He showed by calculations that there is not enough organic matter in the soil to produce average yields of farm crops. The material of importance which comes from the soil, he said, is the mineral matter. Supply the soil with a sufficiency of mineral matter, and it will remain fertile, regardless of its content of organic matter. Such, in brief, was Liebig's mineral theory of plant nutrition. This was a practical theory and easily tested. Liebig himself, as an object lesson, transformed a barren, sandy piece of land near Giessen, Germany, into a beautiful garden, by means of his mineral manures. Mr. John Lawes was incited to begin field experiments at his manor of Rothamsted, England.

These experiments led to the discovery of the process of mak-

ing acid phosphate by treating phosphate rock with sulphuric acid. The process, which was patented, became the foundation of the fertilizer industry. The Rothamsted experiments, probably the most famous field experiments yet instituted, have been carried on with the same applications of fertilizers and manure since 1852. Sir John Lawes endowed the Rothamsted Experiment Station, and made provision for continuing its work indefinitely. The great fertilizer industries, and the era of agricultural experimentation, may be said to date from the application of chemistry to agriculture made by von Liebig in 1840.

Evidence for the Mineral Theory.—As evidence that the organic matter of the soil is not necessary to plants, plants have been grown to full maturity in soils from which all the organic matter had been burned out. Plants were also grown in pure water containing no organic matter, or carbon, to which certain mineral salts had been added. A prize was offered by the University of Göttingen for the solution of the question, whether the ash of plants was taken from the soil or created by them. Such prizes are still offered in Europe. This prize was won by Weigmann and Polstorff.[1] In their first series of experiments, they grew a number of plants of different kinds, upon sand from which the soluble materials had been removed, as far as possible, by extraction with strong acids. One set of plants received only distilled water, the other set received a mixture of the mineral salts found in the ash of plants, and nitrates. The plants which received distilled water hardly grew at all, but the others grew well. This was evidence that the mineral matter was necessary for the growth of the plants. The plants grown on the sand with distilled water alone, when burned, were found to contain slightly more ash than was present in the same quantity of seed from which they were grown. Weigmann and Polstorff thought that this gain came from the sand. They accordingly instituted further experiments and grew plants in a platinum dish on platinum scraps with distilled water, the seed being weighed. Upon incineration, the quantity of ash in the plants was found to be exactly equal to

[1] Dissertation, 1842, cited Meyer's Agricultur Chemie.

the quantity of ash in the seed planted. Hence the plants did not create any ash, and the ash gained in the previous experiment must have come from the sand. This work is an example of the importance of continuing experiments until only one possible conclusion is indicated, and also shows the danger of formulating conclusions upon insufficient data.

The plants in the platinum dish after reaching the height of only two or three inches, began to turn yellow, and died. This showed that the ash in the seed was sufficient for only a limited development of the plant, and, taken in connection with the preceding experiment, showed the mineral matter was necessary to the growth of plants.

Finding the Essential Elements.—An essential element is an element whose presence is absolutely necessary to the full growth and maturity of the plant. A *useful* element, though not essential, may be serviceable to the plant.

The following fourteen elements are invariably present in plants:—

The eight *non-metals*: carbon, hydrogen, oxygen, nitrogen, phosphorus, sulphur, silicion and chlorine.

The six *metals*: potassium, calcium, magnesium, iron, sodium and manganese.

Other elements are sometimes found in plants.[1] Iodine occurs constantly in sea-weeds and sponges, being present as an organic compound in the latter. It is prepared from the ash of sea-weeds. Fluorine, arsenic, boron, rubidium, bromine, lithium, barium, aluminum, thallium, lead, zinc, titanium and copper have also been found in plants, in minute quantities.

Water Culture Experiments.—Experiments to ascertain which elements are essential or useful to plants are made by growing plants in pure water, to which the salts to be tested are added. This is known as the *water culture* method, and is used because it is comparatively easy to secure pure water and salts, but almost impossible to secure a sand or soil from which plants do not ex-

[1] Jahresber. Agr. Chem., 1864, pp. 94, 99, 159; 1866, p. 121. Exp. Sta. Record 3, p. 717; 7, p. 643.

tract some substance. Only the fourteen elements invariably found in plants need be considered, and as two of these (hydrogen and oxygen) are in the water, and one (carbon) is supplied from the air, there remains eleven to be tested. Twelve solutions are prepared. One contains all eleven elements, and is used as a check. If the plant does not thrive in it, something is wrong with the experiment. Each of the other solutions contain salts of ten elements, one being left out of each solution. For ex-

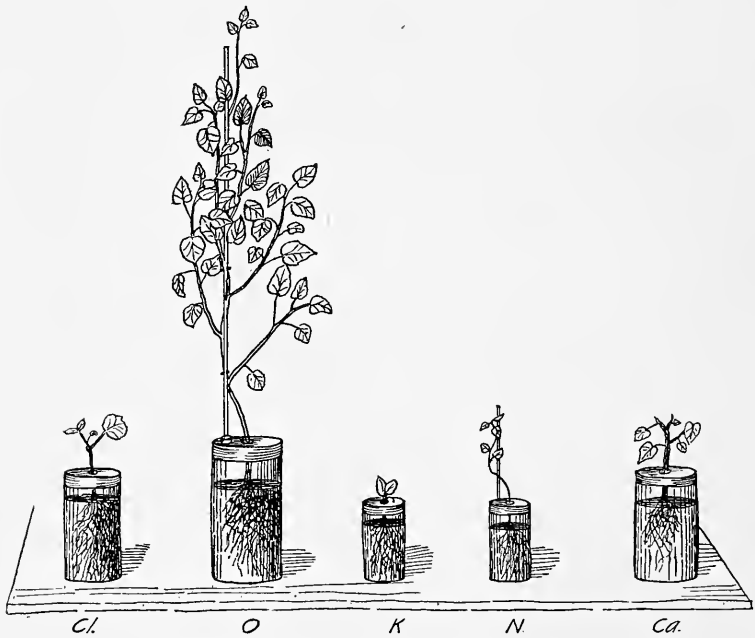


Fig. 1.—Buckwheat grown in complete nutrient solution (O) and with Cl, K, etc., absent.

ample, sodium is left out of one, potassium left out of another, and so on. Seeds are germinated on moist filter paper, and the strongest seedlings are supported by a cleft cork in the neck of the bottle containing the nutrient solution, so that the roots are immersed, but the cotyledons are above the surface. The plants would probably die if the cotyledons were immersed. The vessel

is covered with black paper to exclude light and so prevent the growth of green algae, which interfere with the success of the experiment. The nutrient solution is replaced by a fresh solution every few days, to avoid injury to the plants by change in the chemical composition of the solution. Absorption of excess of acid or basic radicals by the plants, leaves the liquid acid or alkaline, according to its previous composition.

Where the plant grows well, reaches a good size, and produces seed, the element absent from the solution is not essential. Where the plant makes a very poor and imperfect growth, and produces only a few seed, or none at all, the element absent from the solution is essential. Since the seed always contain a certain quantity of the essential elements, some growth of the plant is to be expected.

The results of one series of experiments, are not, of course, considered final. In experimental work, the work of one man has usually to be confirmed by that of others, before it receives general acceptance.

The method of experiment known as "water culture"[1], is suitable for experiments in which the material supplied to the roots must be accurately controlled. It is impossible to secure a soil or a sand from which plants will not obtain some mineral material. Weigmann and Polstorff, as we have seen, found that plants extracted ash from sand which had been exhausted with strong acids, and other workers have had similar experiences. By using pure water and pure salts, we know exactly what material is presented to the roots of the plants. The plant may take up a small portion of the silica from the glass when the experiment is conducted in glass vessels, but this is not usually of importance. If necessary, vessels of platinum or of paraffin, can be used.

The Essential Elements.—It has been found by experiments such as those described above, that the following elements are, without doubt, essential to the life and growth of plants:

The four *metals*: potassium, calcium, magnesium, and iron.

The three *non-metals*: nitrogen, sulphur, and phosphorus.

[1] Knop, Sachs and others, Jahresber. Agr. Chem., 1861, pp. 126, 136.

The *non-metals*: carbon, hydrogen and oxygen, secured from the air and water, as already stated, are essential. A soil, to be fertile, must supply to the plant an abundance of potassium, calcium, magnesium, iron, nitrogen, sulphur, and phosphorus.

Plants can be grown to full maturity by means of the following solution:—

One gram calcium nitrate,
0.25 gram potassium nitrate,
0.25 gram potassium sulphate,
0.25 gram magnesium sulphate,
0.20 gram ferrous phosphate.
1,000 cc distilled water.

Chlorine Essential but Unimportant.—Experiments to ascertain whether or not chlorine is essential to plants were at first conflicting. Three independent investigators grew plants in water culture to full and complete maturity without chlorine. Knop grew corn, buckwheat and cress; Wagner grew corn; and Birner grew oats.

On the other hand, Nobbe and Siegert[1] found that, although buckwheat grew well in water culture without chlorine up to the time of flowering, a little later the tips of the stalks died off, the leaves became brittle, spotted, and fluffy, starch accumulated in the stems and no seed were produced. The diseased condition was remedied by the addition of chlorine. Chlorine thus appeared to be essential to the formation of the seed of buckwheat. Leydhecker[2] also found that buckwheat would not seed in absence of chlorine, and Nobbe later confirmed previous results by a second series of experiments.

Thus one group of investigators finds chlorine not essential, the other group finds that it is essential. These contradictory results are explained by the work of Bayer.[3] Bayer grew oats in water culture, with and without chlorine, all the other essential elements being, of course, present. With chlorine 12.5 grams seed were

[1] Landw, Versuchs-stat., 1863, p. 116; 1865, p. 377.
[2] Ibid, 1866, p. 177.
[3] Landw. Versuchs-stat., 7, p. 370.

secured, without chlorine 7.5 grams of seed. Apparently chlorine was not essential. The seed grown in the absence of chlorine were found, on analysis, to be nearly free from chlorine. These seeds were used in another experiment in water culture as before, with and without chlorine. With chlorine, they made seed; without chlorine, they failed to produce seed. Chlorine, therefore, is essential. The *seed* used in the first series of experiments con-

Fig. 2.—Pot experiment showing soil deficient in nitrogen and in phosphoric acid. Texas Station.

tained a sufficient quantity of chlorine for the full development of the plant, but those used in the second experiment did not.

There are a number of instances in which apparently contradictory results of different workers have been reconciled by further investigation.

The opposite results of the investigators referred to above are due, in one case, to the presence of sufficient chlorine in the seed used; in the other case, to insufficient chlorine in the seed. We may conclude that chlorine is essential to the plant, but the minute quantity required may be present in the seed. Chlorine is

needed in such small quantity that it need hardly be considered as a plant food by the agricultural chemist.

Silicia not Essential but Useful.—Silica is present in all plants grown under normal conditions, and makes up a considerable proportion of the ash of some plants. The ash of cereal straws contain 20 to 40 per cent. It was formerly thought that silica was essential to the strength of cereal straws. Plants have been grown to maturity without silica, though they secured traces from the glass vessels in which the solutions were contained.[1] The plants attained a normal development, and produced seed well. Silica is, therefore, not essential to plant life. Though not essential, silica is useful. In certain water culture experiments by Kreuzhaga and Wolff[2] with oats, the presence of the silica increased both the number and the weight of the seed. The silica appeared to aid the plant to mature and form seed. The following table shows the results of an experiment in which all conditions were constant except the silica:—

	Number of seed	Weight of seed in grams
No silica	715	23
Little silica	1,039	24
Much silica	1,425	46

The silica is supposed to cause the leaves to die off during the ripening of the fruit, allowing essential elements to be withdrawn and utilized in formation of seed. According to Wolff, if silica is absent from the solution, oats will produce empty seed heads unless an excess of phosphoric acid is present. The silica thus economizes phosphoric acid, and this is a highly useful function. Hall and Morison,[3] at the Rothamsted Station, show that silica used as a fertilizer causes an increased yield and earlier formation of the grain of barley, but causes the plant to take up more phosphoric acid from the soil.

Soda Not Essential.—Soda is never absent entirely from any

[1] Sachs, Jahresber. Agr. Chem., 1862, p. 97.

[2] Landw. Versuchs-stat., 1884, p. 161.

[3] Proc. Roy. Soc., 1906, p. 445.

plant. It has been impossible to exclude soda completely in water culture experiments, owing to its presence as impurities in reagents, and its entrance into solution by the action of water upon glass vessels, but otherwise such experiments show that soda is not essential. Soda does not appear to perform any such highly useful functions as silica. It may, however, take the place of the indifferent essential ash, and so replace potash.

Definition of Plant Food.—Plant food may be defined as any substance which contributes to the building of tissue or is otherwise essential to the life of plants. Carbon dioxide, which is assimilated by the leaves, is plant food, and so is water. But we are more concerned in agriculture with the mineral salts which enter the roots of plants, since these require control and are more or less subject to it, and we have these in mind rather than carbon dioxide or water when we speak of plant food. By plant food we usually mean potash, phosphoric acid, nitrogen, sulphates, lime, magnesia, or iron. Often the term is confined to nitrogen, phosphoric acid, and potash, for the reason that they are the only forms of plant food commonly added to the soil.

We have spoken of the *elements* essential to plants, but we must bear in mind that the *free* elements, with two exceptions, are useless to plants. These two exceptions are oxygen, which is given off by plants to a much greater extent that it is used, and nitrogen, which in the free state can be taken up by leguminous plants, if the bacteria which aid in this process are present. All the other elements in the free state are either useless or injurious to plants. The essential elements must be present in certain forms of combination; other combinations are injurious or useless. These facts have been ascertained by numerous experiments with water cultures and sand cultures.

Iron is taken up as ferric compounds; ferrous compounds are often injurious. Phosphorus must be present as phosphates, sulphur as sulphates, chlorine as chlorides, silica as silicates or silicic acid. Sulphides, sulphites, chlorates, and perchlorates, are injurious to plants. Carbon is absorbed as carbon dioxide, and as organic bodies to a much less extent. Oxygen

is taken up in water, in carbon dioxide, and as free oxygen. Nitrogen enters the plant in nitrates, ammonia, as free nitrogen, and to some slight extent in organic bodies. Hydrogen is taken up as water and ammonia. Since these elements are present in the soil in the oxidized condition, and are taken up by plants in that form, and not as elements, plant food is usually referred to and estimated in the form of the oxides. We speak of phosphoric acid (P_2O_5), potash (K_2O), soda (Na_2O), lime (CaO), magnesia (MgO), oxide of iron (Fe_2O_3) and silica (SiO_2). These terms are used almost exclusively in agriculture and especially in the analysis of soils and fertilizers. We speak of nitrogen (N) and chlorine (Cl), for the former may or may not be present in the oxidized condition, and the latter is injurious when oxidized.

Quantity of Plant Food Required.—The method of determining the exact quantity of plant food required is tedious and difficult and has been applied only to two or three plants.

To determine the minimum quantity of phosphoric acid required by oats, Wolff[1] grew eight sets of six oat plants each in water cultures. One solution contained an excess of all the essential forms of plant food, except phosphoric acid. The other solutions received increasing amounts of phosphoric acid. All conditions were the same, excepting the varying amounts of phosphoric acid. When the oats were ripe, they were harvested and subjected to analysis. The following are some of the results:

Phosphoric acid in Mgr. Per vessel	Weight of crop in grams		Phosphoric acid in dry matter per cent.
	Grain	Straw	
230.4	5.8	11.0	1.11
155.4	3.4	10.9	0.83
97.9	2.7	11.1	0.53
49.4	2.5	10.2	0.33
33.0	1.8	7.2	0.28
24.8	1.8	5.2	0.27
14.8	1.0	3.0	0.27
0.0	0.3	1.1	0.27

[1] Jahresber. Agr. Chem., 1873, p. 293.

When the plant contained less than 0.33 per cent. of phosphoric acid, it was not well developed. When the percentage of phosphoric acid was increased over 0.33 per cent., the quantity of straw was little affected, but the quantity of grain increased. In the presence of silica, equally as much grain could be produced with 0.33 per cent. phosphoric acid. Wolff therefore concludes that the minimum quantity of phosphoric acid required by the entire oat plant is 0.33 per cent. of the dry material.

Similar series of experiments were made with potash, lime, and other forms of plant food. From these experiments Wolff[1] concludes that the minimum requirements of the oat plant, based on the dry matter of the entire plant, is as follows:—

	Per cent.
Phosphoric acid	0.35
Potash	0.8
Lime	0.2
Magnesia	0.2
Sulphuric acid	0.2
Total of the essential constituents	1.75
Pure ash necessary	3.00
Nitrogen	1.00

While the oat plant can get along with 1.75 per cent. of the essential ash constituents, a total of 3.00 per cent. of pure ash is absolutely necessary. It was impossible to grow a plant with less than 3.00 per cent. of ash. The additional 1.25 per cent. may consist either of essential elements, or of unessential elements, such as silica or soda, but the quantity required must be made up in some way or other. We may term the ash in excess of the sum of the essential ash ingredients, the *indifferent ash.* The unessential elements can be useful to the plant in making up its indifferent ash, which is, however, essential. Various substances sometimes added to the soil, such as salt, gypsum, lime, etc., may be useful in satisfying the need of the plant for indifferent ash. Since 1.25 per cent. of the necessary 3.00 per cent. of the ash of oats may be of varying nature, and since plants may take up ash in excess of their needs, the ash of the plant is subject to considerable variation in composition.

[1] Jahresber. Agr. Chem., 1875, p. 251.

Quantity of Plant Food Needed by Plants.—The experiments by Wolff already cited show the minimum requirements of the oat plant, but this method has not been applied to other plants, and we are dependent upon other methods for ascertaining the needs of the plant. The only other method which has been used is to make the analysis of the plant.

This is not altogether a safe guide: first, because plants may take up an excess of plant food; and secondly, near maturity material is easily washed from the leaves and other parts of the plant by rain, dew, etc., as shown by LeClerc and Breazeale.[1] For estimating the draft of the plant on the soil, analysis is of course more satisfactory. Such analyses are also used for calculating the manurial value of feeds. Most of the estimations of the mineral matter in plants have been made by analyses of the ash. Nitrogen is determined on a separate sample of the original plant material.

The Ash of Plants.—When plant substance is burned, the greater portion of it passes off as volatile bodies. The residue is termed the *ash*. The ash is sometimes spoken of as the mineral part of the plant, or the inorganic part. These terms are not correct. The ash is merely that portion of the plant which forms compounds not volatile at the temperature of the combustion. A portion of it may have been present in the plant in the form of inorganic bodies, and a portion has undoubtedly been in organic combination.

The term *crude ash* is applied to the ash as secured by burning. *Pure ash,* or *carbon free ash,* is the crude ash less the free carbon, carbon dioxide, and sand contained in it.

Under ordinary conditions, all of the nitrogen and hydrogen, most of the carbon and oxygen, a considerable part of the sulphur, and a small portion of the potash and chlorine pass off during combustion. The ash consists chiefly of carbonates, oxides, sulphates, phosphates, silicates, and chlorides of potash, lime, magnesia, and soda. Unburned carbon is usually present, and in rare cases cyanides and sulphides are found. The fact that a

[1] Yearbook, U. S. Department Agriculture, 1908, p. 389.

large part of the sulphur is volatilized was overlooked for a long time. For example, the following results[1] were obtained:—

	Percentage of SO_3 in	
	Cowpeas	Corn
Sulphur in ash	0.08	0.01
Total sulphur as actually present	0.47	0.39
Loss by burning per cent	84.0	97.0

The result has been that the draft of the plant on the sulphur in the soil has been decidedly under-estimated, and it is quite possible that some soils may be deficient in sulphur.[2]

Variations in Ash.[3]—The percentage and composition of the ash of plants varies according to the kind of plant, the part of the plant, the stage of growth, the variety of the plant, the soil, the season, and other conditions.

Seeds contain plant food stored for the benefit of the young plant, and are less variable in composition than any other portion of the plant. Although they contain comparatively small quantities of ash, the ash is rich in the essential plant foods. The pure ash is composed largely of phosphoric acid, from 30 to 50 per cent.; potash, about 30 per cent.; magnesia, about 8 to 15 per cent. Lime is present in comparatively small quantity, and little or no silica is found, except in the case of oats or similar plants where the husk or chaff is included in the analysis. (See table below). Leguminous seeds appear to be richer in potash and poorer in lime than the seed of cereals.

Roots and tubers, which, like seeds, contain a reserve store of material for the use of the plant, are also rich in valuable plant food, though more variable in composition than seeds. Unlike seeds, the ash carries considerably more potash than phosphoric acid; but, like seeds, it contains more magnesia than lime.

Leaves of plants are very variable in composition. The ash

[1] Fraps, Jour. Am. Chem. Soc., 23, 199.

[2] Jour. Agr. Sci., 1, p. 217.

[3] See Wolff, Ashen Analysen. Also Tollens, Exp. Sta. Record 13, pp. 207, 303.

is rich in potash and lime, but contains much smaller quantities of magnesia and phosphoric acid. The quantity of silica is larger than in the ash of seeds or tubers, being slightly less than the phosphoric acid.

Cereal straws are variable in ash content, though the ash is considerably lower than in leaves. The ash is very rich in silica, and contains fair amounts of potash. Its content of lime and magnesia is comparatively small, and it contains about half as much phosphoric acid as leaves. Like leaves, cereal straws contain more lime than magnesia.

Leguminous straws resemble leaves closely. The ash is rich in lime and potash, and contains approximately the same amounts of phosphoric acid and magnesia as the ash of leaves.

AVERAGE AMOUNT OF ASH CONSTITUENTS IN 1000 PARTS BY WEIGHT OF THE DRY SUBSTANCE.

Number Averaged		Pure ash	Potash	Lime	Magnesia	Phosphoric acid	Silica
	Hay and Grasses—						
106	Meadow hay	69.8	18.6	11.1	4.8	5.0	20.0
7	Green corn (in bloom)	60.6	21.5	8.3	6.5	6.1	11.0
13	Sugar cane	23.6	4.6	1.9	1.8	1.6	10.3
113	Red clover	68.6	22.2	24.0	7.5	6.6	1.9
12	Alfalfa	73.8	17.4	30.0	3.6	6.3	7.0
17	Buckwheat	82.3	25.4	33.2	10.9	5.0	0.9
	Seeds and Fruits—						
110	Winter wheat	19.6	6.1	0.6	2.4	9.3	0.4
36	Winter rye	20.9	6.7	0.6	2.4	10.0	0.3
57	Summer barley	26.1	5.6	0.7	2.3	9.2	6.7
57	Oats	31.2	5.6	1.1	2.2	8.0	12.2
15	Corn	14.5	4.3	0.3	2.3	6.6	0.3
3	Buckwheat	13.7	3.2	0.6	1.7	6.7	0.3
40	Peas	27.3	11.8	1.3	2.2	9.8	0.3
	Cotton	39.8	12.9	2.8	6.2	13.9	0.6
	Straw—						
18	Winter wheat	53.7	7.3	3.1	1.3	2.6	36.3
25	Winter rye	44.6	10.1	3.7	1.4	2.9	22.0
38	Oats	71.7	20.6	5.0	2.6	3.3	33.5
	Roots and Tubers—						
59	Potatoes	37.9	22.8	1.0	1.9	6.4	0.8
149	Sugar beet	38.3	20.4	2.3	3.0	4.7	0.9
32	Turnips	80.1	36.4	8.5	3.0	10.2	1.5

Effect of the Soil and Season.—The character of the soil and the weather conditions prevailing during the growth of plants, have a great influence upon the composition of their ash. The seed is less influenced by these conditions, but the straw of cereals is greatly affected. Indeed, it has been proposed to determine the needs of the soil for plant food by analysis of certain plants grown on it.

At the Rothamsted Experiment Station, barley has been grown on a certain field for over fifty years. Some of the plots receive no fertilizer, and others receive various mixtures, but the treatment has been the same during the entire period. Plots which do not receive the complete fertilizer should be depleted of the plant food not added in the fertilizer. There is very little variation in the composition of the ash of the grain. The phosphoric acid and silica in the straw vary slightly, but great changes take place in the percentages of potash and soda.

	Percentage composition of barley ash, grown 40 years without potash[1]	
	Potash	Soda
Average 10 years 1852-61	18.4	6.4
Average 10 years 1862-71	13.3	11.4
Average 10 years 1872-81	9.7	12.7
Average 10 years 1882-91	7.4	11.9
Average 40 years with potash as a fertilizer	31.0	2.2

While the yield of grain decreases from 45.62 to 36.63 bushels per acre, the composition of its ash is little affected. The potash in the ash of the straw decreases from 18.4 per cent. to 7.4 per cent., accompanied by an increase in soda, though not in corresponding quantity. The ash in the straw from the plot receiving potash fertilizers contains four times as large a percentage of potash as ash of the straw produced without potash during the decade 1882-91. Since in the first two ten-year periods about 2,700 pounds straw per acre was produced on the no-potash plot, while the 40 year average for the potash plot is 2587 pounds,

[1] Agricultural Investigations at Rothamsted, Gilbert, Bulletin 22, Office of Exp. Station, U. S. Dept. Agr., page 78.

it is evident that the higher percentage of potash did not contribute to a greater production of straw. That is to say, *plants may take up a considerable excess of plant food,* especially of potash.[1]

The influence of the season upon the ash content of plants is illustrated by the same series of analyses referred to above, namely, barley grown on the experimental plots of the Rothamsted Experiment Station. The differences between the *average* composition of the ash of plants from plots differently manured, show the effect of the application of plant food. The differences between the highest and lowest content of ash for the same manure, show the effect of the season. The results in the following table are expressed in terms of the *plant* instead of the *ash* as in previous tables.

EFFECT OF MANURES AND THE SEASON ON POTASH AND PHOSPHORIC ACID CONTENT OF BARLEY.

	Potash and phosphoric acid in 1000 parts dry matter of the plant[2]					
	Potash			Phosphoric acid		
	Highest	Lowest	Average	Highest	Lowest	Average
Grain—						
Unmanured	7.7	6.0	6.5	10.1	8.9	9.3
Farm yard manure	8.4	5.9	6.8	10.5	9.2	10.0
Complete fertilizer	8.0	5.6	6.6	10.4	8.8	9.6
Straw—						
Unmanured	11.8	5.3	8.6	2.6	1.2	1.7
Farm yard manure	22.0	6.8	13.2	2 9	1.5	2.2
Complete fertilizer	22.5	5.7	14.1	3.1	1.1	1.9

Both fertilizer and season have comparatively little effect upon the composition of the grain, as we have observed before. On the straw, the season has a greater effect than the fertilizer. For example, the average potash in the unmanured straw is to the potash in the manured straws as 8.60:14.10 or less than 1:2, while in different seasons the straw grown on the manured plot varied

[1] See also Wilfarth and Wimmer, Exp. Sta. Record 13, 1030.

[2] Bulletin 22, Office of Exp. Station, p. 75.

in potash from 6.8 : 22.00 or over 1 : 3. Inspection of the table shows that phosphoric acid varies in a similar manner, though the variations are not so large. In these experiments, at least, *the effect of the season is greater than the effect of fertilizers or the soil.*

Ash of Strong and Weak Plants.—Various chemists have selected strong plants and weak plants growing in the same field at the same time, and subjected them to analysis. Some analyses of this kind are given in the following table[1] :—

COMPOSITION OF STRONG AND WEAK PLANTS.

	Pure ash in plant	Percentage Composition of ash					
		Potash	Lime	Magnesia	Oxide of iron	Phosphoric acid	Silica
Winter wheat—							
Strong plants .	8.04	43.07	6.40	3.60	0.20	7.08	32.82
Weak plants ..	7.55	32.89	3.73	2.30	0.20	8.20	48.40
Oats—							
Strong plants .	8.03	43.15	7.02	4.50	0.50	7.28	20.86
Weak plants ..	6.48	39.35	6.06	3.30	0.60	7.68	34.18
Barley—							
Strong plants .	10.83	43.10	8.73	3.83	0.60	7.33	18.67
Weak plants ..	8.39	38.15	7.33	3.77	0.60	8.20	30.50

The weak plants contain a smaller percentage of ash than the strong plants. The percentages of potash and lime are smaller, and the percentages of silica are much larger in the ash of the weak plants.

Effect of Stage of Growth on Ash.—The percentage of ash shows the relation between the organic matter formed and mineral matter taken up by the plant. The absorption of mineral matter from the soil, and the production of organic matter by the plant, do not proceed at the same rate, consequently the percentage of ash in the plant varies at different periods of time. Changes in the ash content of plants at different periods of growth depend upon the kind of plant, and the part of the plant under consideration. As a general rule, we find that the ash content is greatest in the young plant, and that it decreases with the

[1] Wolff's Ashen Analysen.

age of the plant. That is to say, the young plant takes up more mineral matter in proportion to the quantity of organic matter it elaborates, than the older plant.

The nature of the soil also affects the changes in the ash of a plant during its growth. When an insufficient quantity of plant food is supplied by the soil, the plant may withdraw ash ingredients from its older parts for use in continuing its growth. As we have seen, in the presence of an excess of plant food, the plant may take up more ash than it needs. These facts should be borne in mind in considering the changes in the ash ingredients during the growth of plants. The composition of the plant at different stages on one soil, under one set of conditions, may be quite different from the same plant grown on another soil under another set of conditions. When the plant approaches maturity, ash may be washed out by rain.

For the reasons just given, the following general statements may not apply to individual cases. With the entire plant, the percentage of potash in the ash decreases almost invariably, while, as a rule, silica increases, magnesia increases, lime decreases, and phosphoric acid decreases in some cases and in others increases.

The above statements are made with respect to the entire plant. Exceptions occur with certain parts of the plant, as, for example, the ears of oats.

An example is presented in the following table. Samples of the entire wheat plant were collected at different periods of growth and subjected to analysis by Pierre:[1]

EFFECT OF STAGE OF GROWTH ON ASH OF PLANTS.

Stage of growth	Pure ash in plant Per cent.	Percentage composition of ash				
		Potash	Lime	Magnesia	Phosphoric acid	Silica
Heads appearing	7.4	22.8	20.7	3.8	10.1	35.2
Before bloom	6.5	15.2	17.5	4.2	9.1	45.0
Beginning of bloom	5.3	13.5	13.7	2.7	6.1	55.9
End of bloom	5.1	13.0	11.5	2.7	5.6	58.3
Grains still soft	4 8	10.2	12.4	2.2	5.3	62.5
Ripe	4.7	10.2	10.1	2.4	5.9	64.7

[1] Wolff's Ashen Analysen.

As the grain ripens, and the proportion of seed to husk increases, a decrease in the percentage of silica in the ash occurs.

Ratio of the Essential Elements.—The ratio of the essential elements affects the development of the plant to some extent. Director Hall[1] of the Rothamsted Station states that where barley is grown on the plots fertilized with potash and nitrogen without phosphoric acid, the grain hardly matures at all, while the phosphoric acid in the absence of nitrogen and potash causes the grain to ripen early.

Starting with the fact that lime predominates in leaves while magnesia is in excess in seeds, May, under the direction of Loew,[2] grew tobacco in sand culture with excess of lime and with excess of magnesia, producing in the first experiment a large development of leaves, in the second a very small plant. According to other experiments of Loew and his pupils, the ratio of lime to magnesia is of importance.

For example, Aso[3] grew rice with various ratios of lime to magnesia. The lime and magnesia originally in the soil were estimated by extracting the soil for 24 hours with cold 10 per cent. hydrochloric acid. Such additions of carbonate of lime or carbonate of magnesia were then made to various pots containing 7 kilograms of the soil as were necessary to secure the desired ratios of lime to magnesia. In order to ensure an abundance of plant food, each pot also received 15 grams ammonium sulphate, 15 grams sodium phosphate, and 15 grams potassium carbonate.

The following are the results of this experiment:

Ratio of lime to magnesia	Weight of grain in grams	Weight of straw in grams
5 : 1	20.5	53.5
4 : 1	30.5	59.5
3 : 1	44.0	65.5
2 : 1	58.5	69.0
1 : 1	98.5	125.0
1 : 2	84.0	95.0
1 : 3	79.0	106.0

[1] Rothamsted Experiments, p. 80.
[2] Bulletin No. 1, Bureau Plant Industry, U. S. Dept. Agr.
[3] Bulletin Tokyo Imp. Uni., 1904, p. 97.

According to this experiment, the ratio of 1 part lime to 1 part magnesia is most favorable to the growth of rice. An increase or decrease in the ratio reduces the yield, an excess of lime being more injurious than any excess of magnesia.

Fig. 3.—Upper tobacco plant has excess of magnesia, lower plant excess of lime. Loew. U. S. D. A.

In other experiments Loew[1] found the most favorable ratio of lime to magnesia for some other plants to be as follows:—

[1] Bul. Col. Agr. Imp. Univ. Tokyo, 1902, p. 381.

Lime : Magnesia : : 1 : 1 for oats,
: : 2 : 1 for barley,
: : 3 : 1 for wheat.

Lime,[1] he says, is required for foliage, and magnesia for seed; the greater the proportion of foliage to seed, the greater the ratio of lime to magnesia required by the plant.

Several factors operate to prevent injury by an unfavorable ratio of plant food in the soil. The root of the plant exercises a certain degree of selection by which it may to some extent decline to absorb undesirable plant food. In some plants an excess of lime is deposited in cells in the form of calcium oxalate, in others, it forms a white coating (probably carbonate of lime) upon the leaves. There is a difference of opinion as to the significance of Loew's work. According to Hopkins' experiments,[2] the *quantity* of lime and magnesia are of more importance than the *ratio*.

The importance of the ratio of lime to magnesia in practical farming remains to be decided by field experiments.

Plant Stimulants.—Substances which exert an appreciably favorable action upon plant growth and at the same time are not essential to the life of the plant, may be termed *stimulating compounds*. According to Loew[3] and his pupils, borax and salts of lithium, caesium, uranium, manganese, bromine, iodine, fluorine, and ferrous iron act as plant stimulants in small doses; in large quantities, they may prove injurious. The more important of these stimulants[4] appear to be manganese, iron, and fluorine. It is also possible that certain organic substances may act as stimulants in small doses, or as poisons in large doses. According to Loew, the favorable quantity of the stimulants named is as follows:—Manganous sulphate about 75 pounds

[1] See also Circ. No. 10, Porto Rico Exp. Sta.: Bul. 45, Bureau of Plant Industry.

[2] Soil Fertility and Permanent Agriculture, p. 170.

[3] Bul. Tokyo Univ., 1904, p. 163.

[4] Int. Cong. App. Chem., 1912, 15, p. 39.

per acre; manganous chloride 60 pounds; potassium iodide one-third ounce; sodium fluoride one ounce.

The importance of these stimulating compounds in practical agriculture remains to be demonstrated. Such field tests as have come to the notice of the writer are contradictory. It has been suggested that the copper hydroxide and similar substances used for combating certain plant diseases, instead of killing the fungus direct, stimulate the plant and increase its vigor sufficiently to resist the disease, but we know of no experiments supporting this hypothesis. It is also possible that "stimulating" compounds may occur in certain soils in quantity sufficient to be injurious.

Essentials for Plant Life in Addition to Food.—Conditions other than plant food which are essential to plant life are mentioned here for the sake of completeness. The requirements of foliage, fruit, or roots are different, but the entire plant suffers if a part suffers.

Water, in considerable quantity, is essential to plant life. Only a small portion of the water used by a plant is used as plant food and goes to the formation of organic material. Most of it is evaporated by the leaves of the plant.

Light is essential to the formation of organic matter by the leaves of plants. Too much or too little light affects the development of the plant. Plants vary in their requirements for light.

Temperature.—Extremes of heat and of cold destroy plants. For their best growth a certain temperature is most favorable, and it varies with the kind of plant. Temperatures which do not destroy the plant may yet interfere with its growth.

Favorable soil conditions are essential; the proper degree of moisture, of soil atmosphere, absence of deleterious influences, etc., are necessary to the best growth.

The Law of Minimum.—In the experiment of Wolff on oats, cited previously, the size of the oat crop varied with the quantity of phosphoric acid supplied to it, other conditions being favorable. In the following experiment of Hellriegel,[1] various

[1] Exp. Station Record, 1893-4, p. 853.

quantities of nitrogen were added to a soil provided with an abundance of all other forms of plant food, all other conditions being favorable. The harvest of the barley gave the following results:—

Grams nitrogen supplied per pot	Grams dry matter produced per pot
0.000	0.50
0.028	2.99
0.056	5.32
0.112	10.80
0.168	16.38
0.224	21.72

The size of the crop increases with the quantity of nitrogen at the disposal of the plant. The size of the crop thus varies with the quantity of the most deficient form of plant food. The plant food is the controlling condition in these experiments. Plant food, however, is only one requirement of plant life. The amount of the crop is profoundly influenced by rainfall, temperature, and other weather conditions which are embraced under the term season, as well as by the nature of the soil, etc.

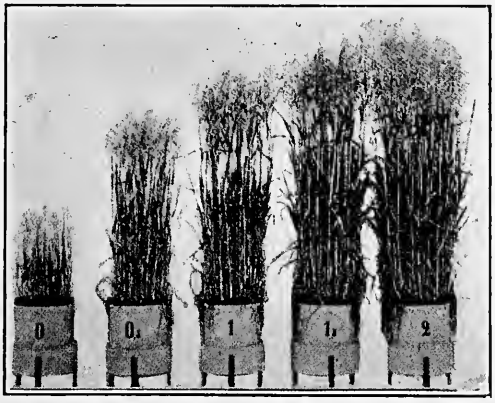


Fig. 4.—The growth of oats is proportional to the supply of nitrate of soda, other conditions being favorable (after Wagner).

The law of minimum holds that the size of the crop is regulated by the condition least favorable to the growth of the plant.

For instance, suppose all conditions were favorable to the production of 100 bushels of corn, with the exception of phosphoric acid; then the size of the crop would depend upon the quantity of phosphoric acid it could secure; if only enough for 10 bushels, then ten bushels it would be. Suppose the soil were very rich, as it often is in arid regions, and there were little water, then quantity of water would limit the size of the crop. An excess of water would also limit—decrease—the crop. If all conditions of soil and water were favorable, the limiting conditions might be the quantity of light the plant received, the temperature, or the individuality of the plant.

The conditions which limit plant growth may be kind of seed, light, water, space, temperature, total ash, phosphoric acid or any other plant food, insects, injurious diseases, or the condition, nature or situation of the soil. The size of the crop depends upon the least favorable of the conditions which surround it. It is exceedingly important in practical agriculture to ascertain the limiting conditions, and render them more favorable.

Mitscherlich[1] gives mathematical expression to the law of minimum. Under ideal conditions, a certain maximum yield would be obtained. The yield is depressed if some essential factor is deficient. If now the deficiency is overcome to a certain extent, the yield becomes greater, and is the larger, the greater the previous depression. According to Mitscherlich, the increase in crop produced by a unit increment of the lacking factor is proportional to the decrement from the maximum. The mathematical expression is:

$$\frac{dy}{dx} = (A - y)k \text{ or } \log_e(A - y) = c - kx.$$

When x is the amount of the factor present, y is the yield, and A is the maximum yield possible with an excess of the factor.

Permanent and Variable Limiting Conditions.—The character of the soil and the plant food which it supplies are more or less permanent during the growth of the crop, but the soil moisture and the weather conditions are more variable. The limiting con-

[1] Landw. Versuchs-stat., 1911, p. 231.

ditions of plant growth are therefore more or less variable, according as moisture or weather conditions are more or less favorable to growth than are soil conditions. The rate of growth, for example, may at one time be controlled by the phosphoric acid supply of the soil, and at another by decrease in the rate of supply of moisture (drought) or by an excess of water or by too cool a temperature, or too little sunlight, etc. The conditions of the soil and its supply of plant food are more or less affected by soil moisture, weather, or other conditions.

The varying effect of the season upon plots with different fertilizer applications, may be seen by comparing the yield of wheat in a wet year and in a dry year, with the average for 51 years, on the plots at Rothamsted,[1] England.

Treatment	Yield of wheat in bushels per acre		
	Average	Wet year	Dry year
No addition	13.1	4.5	10.7
Acid phosphate and potash salts	14.9	5.6	14.2
Acid phosphate, potash salts, sulphate of ammonia	24.0	10.5	19.4
Acid phosphate, potash salts, nitrates	33.8	17.9	21.9
Ammonium salts alone	20.7	4.3	8.4
Nitrate alone	22.7	4.6	10.0
Farmyard manure	35.7	16.0	34.2

There is nearly as much difference between the average crop on the farm-yard manured plot, and the crop during the wet season, as there is between the average yield with no addition, and with the farm-yard manure.

Limiting Conditions are Dependent Variables.—The limiting conditions are not independent of one another, but to a certain extent influence each other so that variation in one may affect several.[2] Increase in water in the soil, for example, decreases the air content, and may decrease soil temperature. By transpiring more water, the plant can take up more plant food. Increase in phosphoric acid of the soil may also increase the activity of the

[1] Hall, an account of the Rothamsted Experiments, p. 54.

[2] Cameron, Proc. Am. Soc. Agron., 1910, p. 102.

soil bacteria, those which convert inert organic matter into nitrates included, and thus increase the supply of plant food. The phosphate added may affect the physical character of the soil. Increase in the soluble plant food in the soil decreases the need of the plant for water and its transpiration becomes less. Increase in temperature increases the action of soil moisture upon plant food constituents, and increases the activity of the soil organisms. Thus a change in one condition of plant life may, and usually does, affect more than one, and the conditions are not absolutely independent.

CHAPTER III.

THE PLANT AND THE ATMOSPHERE.

Although the atmosphere is equally as important as the soil for the production of plants, yet, since atmospheric conditions are little subject to control and are less complex in relation to the plant than soil conditions, much less attention need be given to it. We have already found that the carbon of the plant comes from the air. The atmosphere receives and transports water vapor, and precipitates it in the form of rain or snow. The amount, kind and period of rainfall which are dependent on atmospheric conditions are highly important to agriculture. The atmosphere moderates the variations in temperature. It tempers and stores the heat of the sun. If there were no atmosphere, the temperature would be very hot in the direct sunshine and freezing in the shade.

The soil atmosphere is also of importance. The air penetrates the soil, supplies the roots of plants with the oxygen they need, and oxidizes deleterious substances. It aids in the preparation of plant food so that the plant can take it up. It also aids in the formation of soil from rock.

Composition of the Air.—The air consists chiefly of nitrogen and oxygen. It contains, in addition, a small amount of carbon dioxide, some water vapor, small quantities of argon and allied rare gases, besides minute quantities of ammonia, nitric acid, hydrogen peroxide, and marsh gas. It also contains suspended solid matter, some of which consists of micro-organisms. In towns, the air contains some sulphuric acid and hydrogen sulphide. The moisture in the air varies considerably.

The composition of dry air varies but slightly, even when sampled at widely distant localities. Its average composition by volume is as follows:—

Oxygen	20.90 parts.
Argon	0.90 parts.
Nitrogen	78.15 parts.
Carbon dioxide	0.03 parts.
Hydrogen	0.02 parts.
	100.00 parts.

Carbon Dioxide.—If a vessel of clear lime water is exposed to the air, the lime water after a time becomes cloudy, and a white precipitate or a crust of calcium carbonate is formed. The formation of this precipitate is a test for carbon dioxide, and it is due in this case to the carbon dioxide of the air:

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O.$$

Since plants can be grown to full maturity in water containing certain mineral salts, and the plant contains much more carbon than the seed, while the water does not contain any, it follows that the plant must have taken carbon from the air.

The following is an example of an experiment showing that plants can assimulate carbon dioxide in the presence of light. Boussingault placed a sprig of leaves in a vessel containing 86.5 cc. of a mixture of oxygen and carbon dioxide and exposed it to the sun. After nine hours exposure, the gas was measured and subjected to analysis. The results of the experiment follow:—

	Carbon dioxide	Oxygen
Composition of gas before exposure.....	31.9 cc.	11.5 cc.
After exposure	12.3 cc.	31.4 cc.
Loss.....	19.6 cc.	Gain 19.9 cc.

This shows that the leaves absorbed carbon dioxide and replaced it with a nearly equal volume of oxygen.

Another experiment consists in enclosing the plant in an air-tight vessel, through which air is passed. A known amount of carbon dioxide is added to the air, and the carbon dioxide in the air which passes out is determined. The quantity which disappears is absorbed by the plant. Numerous experiments give the same results. The green leaves of plants absorb carbon dioxide in the presence of light, and replace it with an equal or nearly equal volume of oxygen.

The amount of carbon dioxide in the air can be estimated by drawing a known volume of air first through calcium chloride to remove water, and then through a solution of caustic potash to

absorb the carbon dioxide. The potash bulb is weighed before and after the experiment, and the gain in weight is carbon dioxide. The carbon dioxide may also be absorbed by soda-lime, or by barium hydroxide. Water lost from the absorbing tube is collected in a small tube containing calcium chloride, and weighed with the absorbing tube.

While the percentage of carbon dioxide in the air is small, and is continually depleted by plants during the day, yet the total quantity is large. The income and outgo of the carbon dioxide of the air appear so nearly to balance that no great variation in the amount takes place. The following are the chief processes which restore carbon dioxide to the atmosphere: —

(1) The respiration of animals. Animals absorb oxygen and give off carbon dioxide. The oxidation of organic material derived from food or body substances produces the carbon dioxide.

(2) Combustion. All processes of combustion of organic materials produce carbon dioxide.

(3) Fermentation and decay. These are changes which occur in organic materials, and are usually accompanied by production of carbon dioxide.

(4) Decomposition of calcium bicarbonate by shell fish. The calcium bicarbonate dissolved in the sea water is decomposed, setting carbon dioxide free, and the calcium carbonate is used by the animal to form its shell.

$$Ca(HCO_3)_2 = CaCO_3 + H_2O + CO_2.$$

This carbon dioxide was originally derived from the air.

(5) Dissociation of carbonates by heat, as in the burning of lime. This is a matter of small importance, especially as the lime takes up the carbon dioxide again sooner or later.

$$CaCO_3 = CaO + CO_2$$

Carbon dioxide is also emitted from some volcanoes, deep springs, and other subterranean sources.

Quantity Present.—Country air contains on an average 0.029 per cent. carbon dioxide, or, in round numbers, 3 volumes to 10,000 volumes of air. City air contains larger quantities. Angus

Smith found the air in Glasgow to contain 0.05 per cent. and in London 0.044 per cent. More carbon dioxide is present in the air at night than in the day. For example, Armstrong[1] found the air to contain 0.0296 per cent. carbon dioxide in the day, and 0.330 per cent. at night.

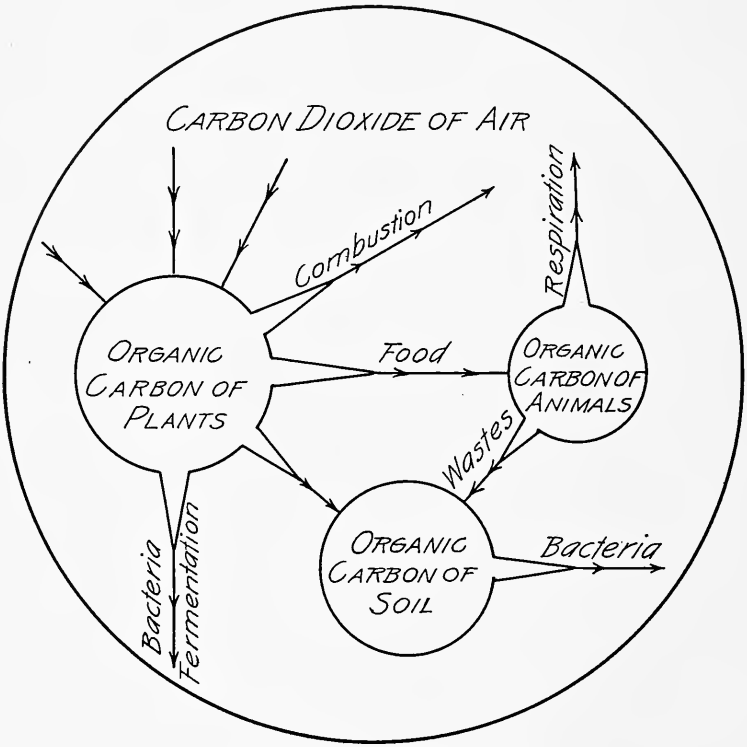


Fig. 5.—Circulation of carbon.

These variations are easily explained. In cities more carbon dioxide is evolved by respiration and combustion than in the country, and less is absorbed by plants. At night the production of carbon dioxide by animals continues, but plants give it off instead of absorbing it, hence the larger amount at night.

[1] Proc. Roy. Soc., 1880, p. 343.

Carbon dioxide is soluble in water, and is brought to the earth with rain. It exerts a solvent action on constituents of soils and rocks, especially on carbonate of lime. The amount of carbon dioxide dissolved by water varies according to temperature and pressure. Carbon dioxide is usually found in springs, wells, and river water, as well as in dew or rain.

Circulation of Carbon.—Carbon circulates from the air to plants, from plants to animals, and from plants and animals back to the air. The oxidation of carbon in decay of organic matter is due to bacteria. The diagram on page 38 illustrates the circulation of carbon.

Effect of Light on Plants.—The energy stored by plants comes for the most part from the sunlight. In the presence of light, green leaves absorb carbon dioxide and give off oxygen. This can be demonstrated by a simple experiment. Some fresh green leaves are placed in a funnel filled with water containing carbon dioxide, inverted in a vessel of water, and placed in the sunlight. Bubbles of gas begin to rise, which may be collected in a small test-tube attached to the stem of the funnel, and tested with a spark on a splinter. This bursts into flame, and so proves the gas to be oxygen.

In darkness, plants take up oxygen and give off carbon dioxide, though the amount is small in comparison with the reverse action in the light. For example, Corenwinder[1] ascertained that three pea plants exhaled 24 cc. carbon dioxide during an entire night, while they absorbed 86 cc. carbon dioxide during an hour of direct sunshine.

The amount of light most favorable to the growth and development of the plant, depends on the kind of plant. Some plants grow better in the sunshine, while others thrive only in the shade. In the diffused light of cloudy days, or the softened light of a forest, plants may exhale either carbon dioxide or oxygen, according to the kind of plant, the intensity of the light, and the stage of development of the plant.

Chlorophyll, the green coloring matter of the leaf, seems to

[1] Jahresber Agr. Chem., 1858, p. 106.

be an essential agent in the decomposition of carbon dioxide and the production of organic matter. Only those parts of the plant which contain chlorophyll are able to assimilate carbon dioxide. If, for any reason, chlorophyll is not formed, assimilation cannot take place. The green color of chlorophyll is sometimes disguised by the presence of other pigments.

Effect of Color of Light.—The effect of light depends upon its color and intensity. The following are outlines of methods for studying the effect of color of light on plants.

(1) Plants may be grown in boxes of different colored glass.[1] This method allows the experiment to be continued any desired length of time. The plants can be then subjected to analysis or otherwise examined. The light which passes through colored

Fig. 6.—Tent for shading tobacco. Pennsylvania station.

glass, is not, however, usually a single color, but is admixed with white or other colors, as can be easily seen by analysis of it with a spectroscope. This is an objection to the method.

(2) A ray of sunlight is decomposed with a prism and the spectrum thrown upon a screen with a slit in it, allowing the

[1] Weber, Jahresber. f. Agr. Chem., 1875-6, p. 336. Flammarion, Exp. Sta. Record 10, p. 103.

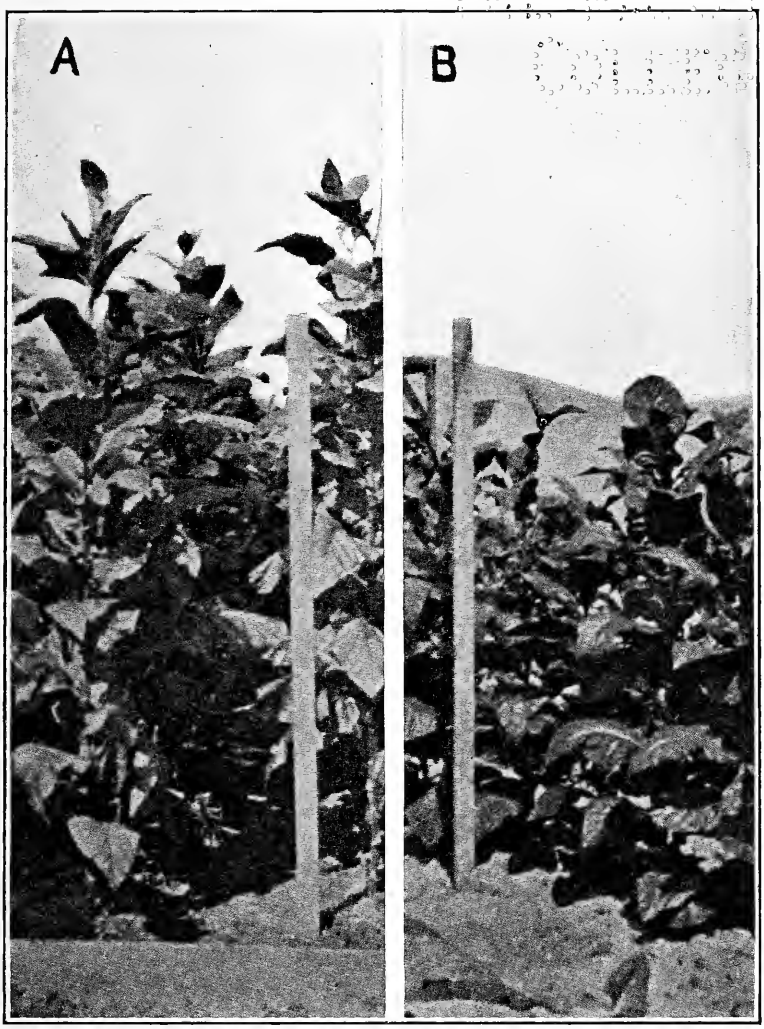


Fig. 7.—Tobacco, (A) shaded; (B) not shaded. Pennsylvania Station.

passage of only one kind of light. This falls upon a leaf placed in water containing carbon dioxide. All the colors except the one to be tested are excluded by the screen.[1] The number of bubbles of oxygen liberated from the leaf in a given time is taken as a measure of the action of the light in producing organic matter by the decomposition of carbon dioxide. More accurate results are secured if the volume of oxygen is measured.

Control of Light.—Only in isolated cases is control of light of practical significance in agriculture. Forcing of early vegetables by artificial light has been tried but has not proved successful enough to be generally adopted. Cigar wrapper tobacco is grown under the shade of cheesecloth or slats.[2] Reduction of light by shading makes the plant grow taller and produce thinner leaves than under ordinary conditions. The thin leaves bring high prices for use as wrappers in making cigars. The shading, however, also modifies moisture and temperature conditions.[3]

Oxygen.—Oxygen is necessary to both animal and plant life. Without oxygen, animals quickly die from suffocation. The oxygen is required by animals for processes of oxidation necessary to life, such as the production of animal heat. The oxygen consumed is replaced by carbon dioxide in the respired air. Oxygen is also consumed in the decay of organic matter, in combustion, and in other processes of oxidation.

The oxygen lost from the air by oxidation is restored by green plants, which, as we have seen, absorb carbon dioxide and evolve oxygen. On account of diffusion and air currents, the quantity of oxygen in the air varies but slightly. In analyses made in widely separated parts of the world, the minimum and maximum amounts of oxygen in pure dry air are 20.53 and 21.03 parts by volume.

Oxygen is necessary for the germination of seeds, for the development of buds, for the roots of certain plants, and for

[1] Pfeffer, Jahresber Agr. Chem., 1870-2, p. 179.

[2] Report No. 62, U. S. Dept. Agr.

[3] Stewart, Bul. 39, Bureau of Soils.

flowers. De Saussure[1] found that buds require oxygen by the following experiment. He enclosed woody twigs cut in the spring just before the time for buds to unfold, in jars containing various gases. In hydrogen or nitrogen the twigs decayed, but in the air

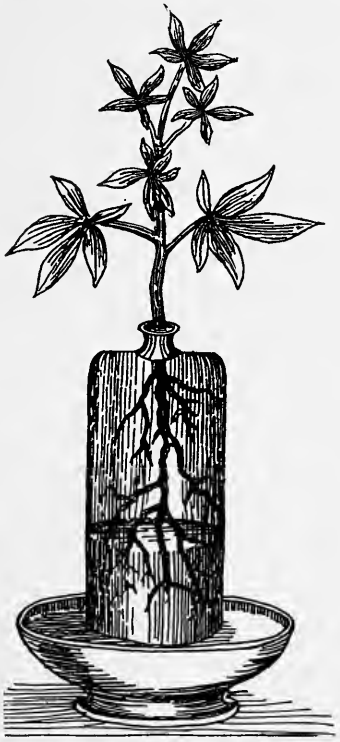


Fig. 8. — Experiment to ascertain the effect of gases on the roots of plants.

the buds opened and, on analysis of the air, oxygen was found to have disappeared. It thus became evident that the buds require oxygen for their development.

In similar experiments with flowers, De Saussure found that they consume several times their volume of oxygen in 24 hours. De Saussure[2] tested the effect of different gases upon roots of

[1] Johnson, How Crops Feed, p. 23.

[2] Johnson, How Crops Feed, p. 24.

plants by cementing the plant in a bell jar, so that the stem and leaves were in the outer air, while the roots were within the vessel and exposed to any gases that might be placed therein. The horse chestnut died in 7 to 8 days when its roots were placed in carbonic acid gas, in from 13 to 14 days in nitrogen, or hydrogen, while the plant remained healthy to the end of the experiment (21 days) when the roots were in contact with air. The experiment shows that the roots of this plant require oxygen, though it lived for some time without oxygen. Other experiments show that roots absorb oxygen and give off carbon dioxide. The roots of some plants, which prefer heavy, wet soils, probably do not require oxygen. The difference in the root requirements of plants for oxygen is probably one factor in their adaptation to various types of soil.

Nitrogen.—The nitrogen of the air, which makes up four-fifths of its volume, is in the free state, and enters into combination only with difficulty. So far as animals and the majority of plants are concerned, the nitrogen of the air serves only as a dilutant for the oxygen, which would have too energetic an oxidizing action if in the pure state.

To be of value to animals or to most cultivated plants, nitrogen must be in combination. This store of combined nitrogen is comparatively small. Plants and the bodies of animals contain some combined nitrogen; there is some in the soil, coal contains a small percentage, and there are some deposits of nitrate of soda. Combined nitrogen is lost when organic matter is burned, any nitrogen present being evolved in the free state. Explosives are rich in nitrogen, which is set free when they are used. In certain processes of decay, free nitrogen is evolved.

The supply of combined nitrogen in the soil is comparatively small, and it is constantly drawn upon by crops. Under our present system of agriculture, the stores of nitrogen in the soil are exploited and depleted. A considerable quantity of nitrogen is washed from the soil by water. Maintaining the fertility of the soil is largely a question of maintaining its store of combined nitrogen. Fortunately, we have now obtained the means for

causing the free nitrogen of the air to enter into combination. The ways at present in which this is accomplished are as follows:—

(1) One process is the assimilation of free nitrogen by bacteria in symbiosis with leguminous plants. This method is the most promising for practical agriculture. The energy of the sun is utilized and the nitrogen is converted directly into organic matter. Some bacteria appear to be able to assimilate nitrogen without the aid of plants.

(2) Another process is the electrical production of nitric acid or nitrates. An electrical discharge is passed through air or through a mixture of nitrogen and oxygen, and the oxides of nitrogen produced thereby are absorbed by water or sodium carbonate or caustic soda. When water is the absorbing medium, nitric acid is produced; if caustic soda or lime is used, nitrates are produced, which may be used as a fertilizer. Since nitric acid is more valuable than nitrate of soda, nitric acid is made when practicable. This method is practicable only when electricity can be produced cheaply, such as is accomplished by water power.

(3) Production of Calcium Cyanamid.[1] Air, freed from oxygen by passing over heated metallic copper, is passed into a mixture of calcium carbonate and carbon heated in the electric furnace. The first product is probably calcium carbide:—

$$2CaCO_3 + 5C = 2CaC_2 + 3CO_2.$$

This is then converted by absorption of nitrogen into calcium cyanamid:

$$CaC_2 + 2N = CaCN_2 + C.$$

The product contains 15 to 25 per cent. nitrogen and is used directly as a fertilizer. A cheap source of electrical energy is required.

Circulation of Nitrogen.—The circulation of nitrogen is somewhat more complicated than that of carbon. The diagram shows the various processes which it undergoes.

[1] Bulletin 63, Bureau of Soils.

Argon, which is found in the air, is a gas related to nitrogen and is apparently incapable of entering into chemical combination. It has no agricultural importance. Associated with argon in the air, in very small quantity, are the other gases of similar character, namely, neon, helium, krypton, and zenon.

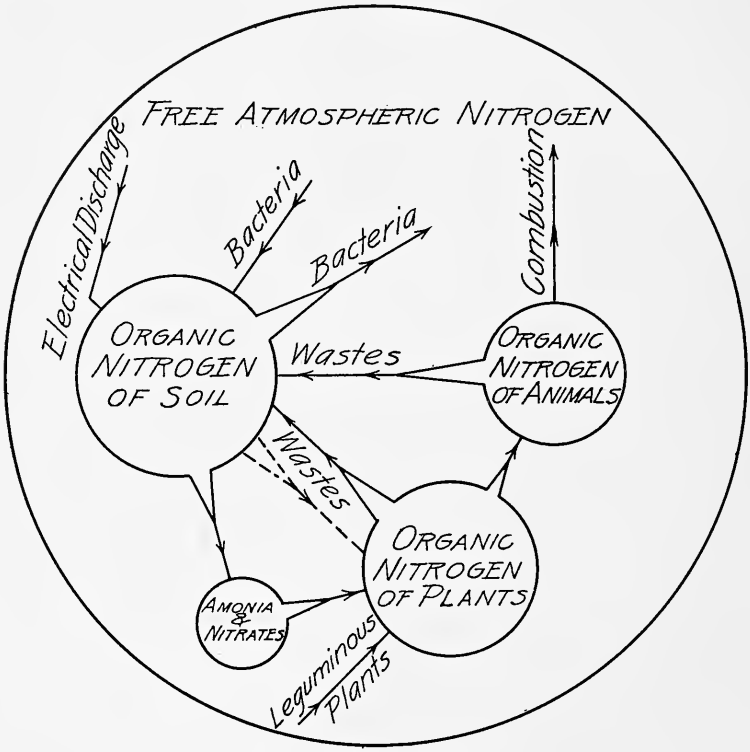


Fig. 9.—Circulation of nitrogen.

Ammonia.—The air contains about one part of ammonia in fifty million. The column of air resting on an acre weighs about 41,300 tons, which would contain about 1.5 pounds ammonia. Country air contains less ammonia than town air. The ammonia in the air probably comes from the decay of organic nitrogenous bodies, especially urine. The exhalations of volcanoes and

fumeroles also contain ammonia, which may be due to the action of water on nitrides.

Ammonia gas is absorbed by the foliage of plants, as has been shown by experiments such as the following of Peters and Sachs.[1] The stem of a bean plant was cemented under a bell jar. The leaves and foliage were within the jar, while the roots and soil were outside. The plant was supplied through tubes with air mixed with 4-5 per cent. carbon dioxide. Another plant in a similar apparatus was supplied with the same gases, but they were passed through a dilute solution of carbonate of ammonia, which gives off ammonia. After two months, the plant supplied with ammonia weighed, when dried thoroughly, 6.74 grams, and contained 0.208 gram nitrogen; the other plant weighed 4.14 grams, and contained 0.106 gram nitrogen. The gain of nitrogen must have been caused by the absorption of ammonia by the foliage of the plant. If the entire plant and the soil in which it grew had been placed in the bell jar, ammonia would have been absorbed by the soil and presented to the roots. But the arrangement of the experiment eliminated this possibility, since the soil and roots did not come in contact with the ammonia at all.

The ammonia of the atmosphere is in such small quantity that it has practically no effect upon plants. This has been shown by experiments such as the following: Hellriegel[2] grew lupines in sterilized sand supplied with all plant food except nitrogen. The nitrogen content of both seed and sand had been previously ascertained by analysis. After the plants had reached their full development, both plants and soil were subjected to analysis, and the amount of nitrogen found was .007 gram less than was present in the seeds planted and in the original soil. The plants, therefore, had lost a small amount of nitrogen, instead of gaining any from the free nitrogen, or from the ammonia of the air.

Nitric Acid.—Nitric acid occurs in the air, probably in combination with ammonia. It is formed by electrical discharges (lightning). The quantity of nitric acid in the air is very small,

[1] Johnson, How Crops Feed, p. 56.

[2] Exp. Sta. Record, 5, 844.

however, and the plants are unable to absorb any appreciable quantity directly from the atmosphere.

Combined Nitrogen in Rain Water.—The atmospheric ammonia and nitric acid are chiefly of importance from the fact that they are brought to the soil in rain, dew or snow, and thereby afford nourishment for plants.

The quantity of combined nitrogen in the rain has been ascertained at a number of Experiment Stations,[1] by determining the quantity and composition of each rainfall. The results of a number of series of observations, each extending over a period of a year or longer, are summarized in the following table:

COMBINED NITROGEN IN RAINFALL PER YEAR IN POUNDS PER ACRE.

	(a) Nitrogen as ammonia	(b) Nitrogen as nitric acid	(a + b) Total combined nitrogen
Temperate Zone—			
Average of 22 places	5.72	2.27	7.99
Maximum (Proskau)	12 95	6.97	19.93
Minimum (New Zealand)	0.50	1.13	1.63
Minimum (Ploty)	3.38	0.24	3.62
Rothamsted, England	2.95	1.13	4.08
Kansas	2.62	1.04	3.66
Tropical Zone—			
Average 8 places	4.26	3.33	7.59
Maximum (Venezuela)	14.05	—	19.25
Maximum (Reunion)	—	6.24	—
Minimum (East Java)	1.13	0.75	1.88

There appears to be considerable variation in the quantity of combined nitrogen brought to the earth by the rain; the average for the temperate zone is 8 pounds per acre. This is sufficient to produce approximately 5.3 bushels of corn, leaves and stalk included. But it is probable that the water which percolates through the soil, in humid regions, takes out more combined nitrogen than is brought down by the rain.

Hydrogen Peroxide.—Country and sea air contains a small quantity of a powerful oxidizing agent, which, according to

[1] Miller, Jour. Agr. Sci., 1905, p. 280.

Schöne,[1] is hydrogen peroxide, though it is often said to be ozone. This substance is destroyed by putrescible substances, and it destroys bacteria. The presence of hydrogen peroxide is thus evidence of the purity of the air as regards freedom from bacteria and putrescible bodies. Hydrogen peroxide does not occur in the air of towns or marshes, since any formed is instantly destroyed by the organic matter present.

At Montsouris, near Paris, the amount of hydrogen peroxide in the air was estimated to be on, an average, about one part in 100,000,000 for a period covering thirteen years.

Hydrogen peroxide may be formed by electrical discharge (lightning) and in some processes of oxidation. It acts upon iodide of potassium, liberating iodine, which turns starch blue. Paper impregnated with potassium iodide and starch is a delicate test for ozone, or hydrogen peroxide, since very small quantities of these substances suffice to turn it blue.

Other Constituents of the Air.—*Marsh gas* (CH_4) is a colorless and odorless gas produced in the decay of vegetable matter under water, as in marshes, and in the digestion of hay and other food by herbivorous animals. Small quantities of it occur in the air.

Sulphur dioxide may occur in the air in the neighborhood of smelters, factories, or in towns. If present in appreciable quantity, it is injurious to vegetation. It is evolved from the oxidation of sulphur during the combustion of coal.

Dust particles, organic matter, and salts from the evaporation of the spray of the sea, are found in the air.

Bacteria are also present, in much greater numbers in the city than in the country. Levy found 345 per cubic meter in the air of Montsouris, 4,790 in the air of Paris (average of 13 years).

Composition of Rain Water.—Rain water has been converted into vapor by the sun, and condensed again into a liquid. In its passage through the air, rain water takes up ammonia, nitrates dust, chlorides and other constituents of the air. Rain water, therefore, though it is the purest natural water, is not absolutely pure.

[1] **Berichte**, 1880, p. 1503.

In exceptional cases it has been known to contain so much dust as to assume a red or black color. It usually contains a small amount of chloride of sodium, and sulphates. The following is a summary of a large number of analyses of rain water made by Angus Smith.[1]

ANALYSES OF RAIN WATER—PARTS PER MILLION.

	Chlorides (as sodium chloride)	Sulphates (as sodium sulphates)	Ammonia	Nitric acid
Scotland—				
Five coast country places ..	20.3	6.4	0.48	0.37
Twelve inland country places	5.6	3.5	0.53	0.31
Six towns	9.7	19.2	3.82	1.16
England—six towns	14.4	60.7	4.99	0.85

We find from the table that the coast rain water contains more salt (sodium chloride) than the rain of inland places. This is due to the salt spray from the sea, which is broken up into fine particles, and carried by air currents for long distances. The effect of the sea upon rain water is often noticeable for a hundred miles inland.

Comparing rain water of the city and of the country, we find that the former is marked by the presence of considerably more sulphates and ammonia, and that it also contains free acid. The increased quantity of sulphates and the sulphuric acid in the rain water of cities can be traced to the combustion of coal containing sulphur.

Arid and Humid Climates.—In a humid climate, the rainfall is sufficient, or more than sufficient, for the production of cultivated crops. In an arid climate the rainfall is insufficient in quantity, and crops can be grown only through irrigation, or by means of special methods of culture. The character of the rainfall also influences the relation of the climate towards crops. A comparatively small amount of rain distributed through the growing season may give a locality the characteristics of a humid region, while a heavier rainfall so distributed that very wet periods are followed by long intervals of little or no precipita-

[1] Jour. Chem. Soc., 1872, p. 33.

tion, may give an arid or semi-arid climate. When the average annual rainfall is 20 inches or below, it is generally assumed that crops cannot be grown without irrigation.

Soil Atmosphere.—The gases which occupy the pores of soils differ in composition from the atmosphere, chiefly in the fact that they contain much more carbon dioxide and less oxygen.

The oxygen of the soil atmosphere performs the following functions:

(1) It oxidizes the organic matter, producing carbon dioxide. Bacteria play an important role in this change. In the absence of air, putrefaction takes place, with production of acid or bad smelling bodies.

(2) It is necessary for the oxidation of organic nitrogen or ammonia to nitrates.

(3) It is necessary for the roots.

(4) It oxidizes partly oxidized mineral compounds, such as ferrous or manganous salts.

The *nitrogen* of the soil atmosphere is fixed by legumes, in co-operation with certain bacteria, producing organic nitrogenous compounds.

The *carbon dioxide* of the soil atmosphere is formed by processes of oxidation, and it is also evolved by the roots of plants. If not removed with sufficient rapidity, it excludes oxygen, and thereby interferes with the normal processes of the soil. The carbon dioxide of the soil increases the solvent action of the soil water, thereby aiding in the disintegration of the minerals of which the soil is composed, and in the solution of plant food.

Processes of Soil Ventilation.—The exchange of gases between the atmosphere and the soil atmosphere depends to a considerable extent upon the character of the soil. A coarse-grained, open soil is much more easily ventilated than heavy, stiff soils. Indeed, it is possible that processes of oxidation take place too rapidly in some porous soils, resulting in the rapid loss of nitrogenous material and consequent poverty of the soil.

The particles of air in the soil tend to move out into the atmos-

phere, and those without move in. This process, known as *diffusion,* though a slow process, aids in soil ventilation.

Air expands when its temperature is raised, and contracts when it cools. These changes also aid in soil ventilation. So do the expansion and contraction resulting from barometric changes. Gusts of wind exert a suctional effect. When water is removed from the soil, air enters in its place.

CHAPTER IV.

ORIGIN OF SOILS.

The soil is the solid outer covering of the earth, which, by being disintegrated into particles, and provided with organic matter and nitrogen, has become capable of sustaining the growth of cultivated plants.

The chemical composition and physical character of the soil are closely related to the material of its origin and its mode of formation.

Geology teaches that ages ago the surface of the earth was a mass of rock, formed by the solidification of molten material. Since then mountain chains have been elevated and razed, and succeeded by new mountains which have been likewise eroded and succeeded by others. Lakes have been filled up or drained, rivers have eroded channels and deposited sediment. Land now dry has been deposited under water. Great changes of climate have occurred. During one period the vegetation was tropical in character. At another time, the climate was colder, and immense sheets of ice covered the northern part of North America. Races of plants and animals have appeared and disappeared. The agencies of the air, and water, have broken up rocks, carried the particles away, and laid them down, perhaps to be formed into rock, elevated into land, and to go through another series of decomposition and rock formation. This process has occurred over and over again. In this way a variety of rocks and a great many soils have been formed.

Soils Formed from Rocks.—Soils are formed by air, water, heat, cold, and plant life, which are termed *weathering agencies,* acting upon rocks. The term rock in the geological sense, means any layer of the earth's crust, whether hard or soft. Thus loose sand and clay are rocks to the geologist as truly as sandstone or granite. The soil chemist, however, does not consider unconsolidated surface deposits as rocks. A deposit formed by wave action, and afterwards elevated so as to become a soil, is not considered as a rock, but as a transported soil.

Weathering agencies act upon consolidated and unconsolidated rocks exposed on the surface of the earth, reduce the size of the particles, and change the rocks chemically and physically. The rocks are changed into soil capable of supporting the growth of cultivated plants.

Broken rocks, however finely pulverized, do not constitute soil. Besides the mere mechanical breaking of the rock, two other processes take part in the conversion of rock into soil. First, a greater or less quantity of organic matter and combined nitrogen are stored up. This process begins with the bare rock. Bacteria first appear. These take up carbon dioxide and nitrogen from the atmosphere and leave organic matter and nitrogen when they die. Then mosses and lichens begin to appear. They also have the power of taking nitrogen from the air. As the weathering agencies deepen the soil, the variety of plants increases, but almost always some of the species are present which have the power of causing atmospheric nitrogen to enter into combination. The residues left when the plants die, store the soil with organic matter and nitrogen. A small amount of organic matter and nitrogen are contained in rocks.[1]

The second change in the conversion of rock to soil is due to the fact that plant food becomes more easily taken up by plants than it was in the original rock. This is in part due to chemical changes, and in part to the action of the organic matter which has been added, but perhaps to the greatest extent to the working over of the plant food by the past generation of plants.

Weathering Agencies.—Weathering is the term applied to the natural decomposition or breaking up of rocks, and weathering agencies are the agencies which do this work. Weathering and weathering agencies are studied by observing the changes which are now going on, and by comparing altered rocks with the original masses from which they were derived.

Weathering processes are both mechanical and chemical. They are mutually helpful. Mechanical processes reduce the size of the rock fragments, thereby affording more surface for chemical

[1] Hall and Miller, Jour. Agr. Sci., 2, p. 343.

action. Chemical processes often disintegrate the rock into very fine particles.

Changes of temperature, moving water, and ice, act mechanically. The chemical agencies are chiefly water and air. Plant and animal life act both mechanically and chemically.

Changes of Temperature.—Changes of temperature act in several ways.

(1) Molten rock masses contract on cooling and become permeated by fissures, cracks, and joints.

Fig. 10.—Rock split by heat and cold.

(2) Water enters into the cracks between rock masses, and, to some extent, into the pores of the rock. When this water freezes, it expands one-fifteenth of its bulk and exerts a tremendous force. It thus splits up rock masses, and disintegrates rocks which are porous.

(3) Rocks are usually composed of two or more minerals, which expand differently under the influence of heat. Heat causes the different minerals to expand and to press on one another, and cold makes them contract and move apart. In time these movements so impair the coherence of the particles as to cause gradual disintegration of the rock.

(4) Large pieces have been observed to split off from bare rocks exposed to the sun. This is due to expansion under the influence of heat, and can take place to any extent only on mountain sides where the fragments fall away from the rock surface.

Moving Water and Ice.—Water, moving from higher to lower levels, uses the rock particles it carries as tools to scour channels even in the hardest rocks. The sides of the channel, being undermined by the stream and loosened by frost, fall into the stream. The rocks grind each other to smaller fragments. All of this material is on its way to the sea or to a lower level and is ground finer as it is carried on.

The rate of movement depends upon the size of the rock, and the size and velocity of the stream. A portion of the material is deposited by the stream, perhaps building up alluvial soils, but sooner or later the stream will begin moving it towards the sea

Fig. 11.—A glacier in the Alps.

again. Water-borne materials are *sorted,* that is, material of nearly the same size is deposited together. Layers of different material may alternate, varying with the velocity of the water current.

Rivers of ice, or glaciers, are formed in very cold climates, or flow from the sheets of perpetual snow covering high mountains. They move slowly, grinding rocks together with enormous force, and form deposits different in character from those of rivers. The fragments are more angular and the deposit consists

of all sizes of particles together. It is said that the Rhone, which is fed chiefly from the glaciers of the Alps, carries such a volume of rock dust that its muddy waters may be traced six or seven miles after they have entered the Mediterranean. The action of glaciers is mechanical; the rock is ground up, but not decomposed.

Chemical Action of Water and Air.—Water acts chemically upon rock-minerals by solution and by hydration. Rain, in passing through the air, dissolves oxygen, carbon dioxide, and other substances. In the soil the water absorbs acids formed by the decay of vegetable matter. These substances aid in its weathering action.

Hydration is a chemical change in which the mineral combines with water. Some minerals take up water, increase in bulk, and fall to a powder. Hydrated silicates are formed from various silicates.

Solution.—There are very few minerals which do not give up a portion of their constituents to water, though the amount of material which goes into solution is usually very small. If pulverized felspar, amphibole, etc., are moistened with pure water, the latter at once dissolves a trace of alkali from the mineral, as shown by its turning red litmus blue. This solvent action is slight on a smooth mass of the material, being limited by the extent of surface. Pulverization, which increases the surface, increases the solvent effect considerably.

This solution involves a chemical change, new bodies with new properties being formed. Carbon dioxide and oxygen aid the action greatly. For example, potash felspar is decomposed by water with the formation of potassium silicate and aluminium silicate. In the presence of carbon dioxide, potassium carbonate is produced and hydrated silica set free, the quantity depending upon the amount of carbon dioxide present. A lime felspar is decomposed in the same way, and the calcium carbonate dissolved by aid of the carbon dioxide the water contains. Silicates of iron are decomposed with the production of hydrated oxides of iron and silicic acid. If the silicate is a ferrous silicate, the iron is oxidized by the oxygen in the water.

Carbonic acid increases the solvent power of water. Rain water contains from 5 to 10 parts (by volume) of carbon dioxide. River and spring waters contain more, but most of it is in combination with lime. The capillary water of soils containing much organic matter, holds more carbonic acid in solution than river or spring water.

Water containing carbon dioxide is especially active in dissolving carbonate of lime or limestone, and removing it from the soil

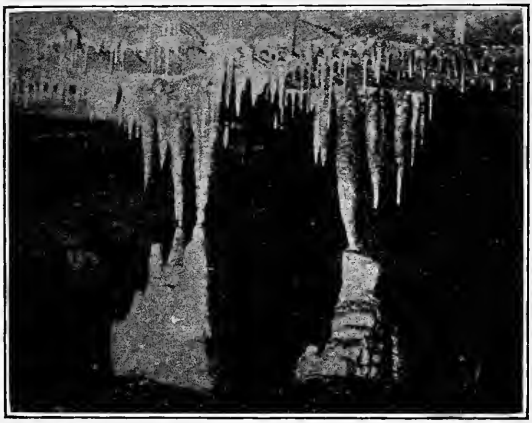


Fig. 12.—Limestone cavern.

or rock. Carbonate of lime is slightly soluble in water (20 parts per million), but much more soluble in water containing carbon dioxide, owing to the formation of calcium bicarbonate:

$$CaCO_3 + H_2O = Ca(HCO_3)_2.$$

Water saturated with carbon dioxide dissolves about 880 parts per million. This solvent action has resulted in the formation of large caverns in limestone regions.

Oxygen is also dissolved in most natural waters, and acts upon the ferrous or manganous compounds which occur in a great number of minerals. When oxidized, these occupy a larger space than before, and thus hasten the disintegration of the minerals containing them. Some ferrous silicates are oxidized rapidly on exposure to moist air, falling into a brown powder in a few weeks.

As a rule, silicates containing much iron are easily changed by weathering agencies.

Action of Animal and Vegetable Life.—Animal and vegetable life act on rocks, both by their living activities and the decay of their remains. Vegetation acts both mechanically and chemically upon the soil and rocks. Roots of plants penetrate the crevices of rocks, and, as they grow, split even large rocks. The shelter of growing plants keeps the rock surface moist, thus enabling the water to act upon the rock, and the carbon dioxide excreted from roots, adds its effect to that derived from other sources. Plants take up material, which, under natural conditions, returns to the soil in a modified form.

Earthworms in some cases bring to the surface large quantities of soil, most of which has passed through their intestines and undergone mechanical and chemical changes.

Vegetable or animal residues aid weathering in several ways:

(*a*) By maintaining more moisture in the surface of the soil.

(*b*) By supplying copious quantities of carbonic acid. The following figures of Boussingault and Levy[1] exhibit the amount of carbonic acid in the air of the soil under different conditions:

	Carbonic acid in 10,000 parts by weight
Ordinary air	6
Air in sandy subsoil of forest	38
Air in loamy subsoil of forest	124
Air in surface soil of forest	130
Air from surface soil of pasture	270
Air from surface soil rich in humus	543
Newly manured sandy field in wet weather	1413

(*c*) By direct action of organic acids such as acetic, propionic, "humic," etc., which are found in vegetable matter or produced in its decay.

(*d*) By furnishing a medium for the activity of the lower soil organisms, such as bacteria and molds.

Products of Weathering.—The general tendency of weathering is towards the production of simpler compounds from more complex ones. The oldest rocks (which are igneous in origin)

[1] Jahresber. der Chem., 1852, p. 783.

contain complex silicates of aluminium, iron, potassium, sodium, lime, etc. The tendency of weathering is to reduce these to simple compounds, such as silica, hydrated oxides of iron, hydrated silicates of aluminium, carbonates or sulphates of lime and magnesia, chlorides of sodium and potassium, and silicates of magnesia. The complex silicates are not changed directly to these simple bodies, but various intermediate products are formed. A long period is required for this process to become complete, so that in many soils all stages of the change may be present, from particles of the original minerals, through various hydrated silicates derived therefrom, down to the simpler compounds. The conditions under which the weathering occurs determine the degree of decomposition. If the weathering agencies are chiefly mechanical, the rock may be reduced to a powder with little chemical change.

Loss of Material by Weathering.—In every case of weathering, a greater or less portion of the constituents of the rock have been carried away. An estimate of the loss may be made where the soil rests directly upon the rock from which it is derived. Samples of the soil, and of the unchanged rock beneath it, are subjected to analysis. We assume one ingredient of the rock has lost nothing in weathering, and calculate the quantity of the original rock containing the amount of this ingredient found in 100 parts of the soil. This gives us the quantity of original rock from which 100 parts of soil was secured. When the composition of both is known, it is a simple matter to calculate the loss of each ingredient.

Suppose, for example, the original rock contained 30 per cent. alumina, and the weathered product contains 45 per cent. alumina. It being assumed that no loss of alumina took place, 150 pounds of the original rock would contain 45 pounds of alumina; that is, 150 pounds has weathered to 100 pounds. If the original rock contained 2 per cent. magnesia, and the weathered product 0.5 per cent., then 150 pounds contained three pounds, and we have 0.5 pound left, giving a loss of five-sixths or 83⅓ per cent. of magnesia. Two assumptions are made in this procedure; one being that some constituent has not been lost

at all, the other being that the rock from which the soil was derived was exactly the same as the underlying rock. As neither assumption is strictly true, the method gives merely approximate results.

The following figures, secured by the method outlined above, are compiled from Merrill's "Rocks, Rock Weathering and Soils."

CALCULATED PERCENTAGE LOSS IN WEATHERING.

	Granite Virginia	Syenite Arkansas	Limestone ?	Basalt Bohemia	Soapstone Maryland
Silica (SiO_2)	52.5	52.3	0	33.1	43.6
Alumina (Al_2O_3)	0	0	11.4	0	0
Ferric oxide (Fe_2O_3)	14.4	86.2	89.6	50.2	41.5
Lime (CaO)	100.0	57.9	98.9	84.5	44.2
Magnesia (MgO)	74.7	82.1	89.4	74.1	76.2
Potash (K_2O)	83.5	81.9	66.3	61.7	47.1
Soda (Na_2O)	95.0	97.1	53.3	—	—

The order in which these constituents are lost varies with the rock and the conditions; the following is the mean order in seven cases:

(1) Lime, (2) potash, (3) magnesia, (4) soda, (5) iron, (6) silica, (7) alumina. That is, the greatest loss is usually of lime, the next greatest is potash, and so on. The figures given in the table preceding are sufficient to show the profound change which may occur in the transformation of rock into soil and the large amount of material which is carried away during weathering, probably for the most part dissolved in water.

Sedentary and Transported Soils.—A sedentary soil is a soil derived from the weathering of a rock in the present location of the soil. On making an excavation, if the soil is sedentary, we find the following: First, the surface soil; then the subsoil, lighter in color but of the same general character; and at a lower depth, we find the subsoil mixed with fragments of partly weathered rock. The fragments increase in quantity until finally we come to the solid rock. We thus observe a gradual transition from soil to rock, and therefore infer that the overlying soil is derived from the decomposition of rock which formerly occu-

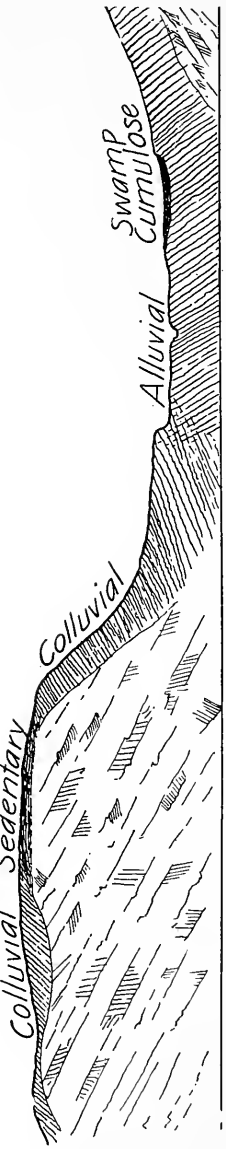


Fig. 13.—Formation of some soils.

pied its position. The soils derived from limestone deposits in Kentucky and in Texas are sedentary, and so are the soils derived from granite and other igneous rocks which are common in the Piedmont plateau of the Atlantic states. Old sedentary soils, from whatever kind of rock derived, are as a rule clays colored by iron. The various mineral constituents are often in an advanced stage of decay, the more soluble constituents having been largely washed out.

A section of the soil may not show a gradual change to the underlying rock, but the change may be abrupt and sudden. Such a soil may be formed when the soil particles are brought from other localities, and deposited, in which case the soil is termed a *transported* soil.

Colluvial and Cumulose Soil.—A colluvial soil is one which has been removed, to some extent, from the original position, so as to mingle with other rocks and layers, as when a soil is washed or moved down hillsides or sloping land. Such soils commonly "creep" or have a slow annual movement. Colluvial soil particles have been partly moved by water, but have not been laid down under water as have alluvial soils. A cumulose soil has been formed by the accumulation of vegetable matter, such as occurs in swamps. Peat and muck are cumulose.

Soils from Igneous Rocks.—Igneous rocks are formed by the cooling of molten matter which has been spread out upon the surface of the earth or injected between layers of other rocks. Metamorphic rocks were laid down by water or other agencies, but were afterwards subjected to such intense heat and pressure as to crystallize minerals in them.

The physical and chemical character of the rock and of the soil which may be derived from it, depends upon its chemical composition, and the rapidity with which the igneous rock solidifies. If the molten mass cools off rapidly, so that it solidifies in a comparatively short time, minerals do not have time to crystallize, and a hard, homogenous, glassy mass is produced (glassy rock). If the molten material remains liquid for a long time and cools slowly, the rock produced is a mixture of definite minerals which can be easily distinguished (crystalline rock).

Other conditions of cooling may give rise to a compact, stony mass, composed of minute crystals (stony rock) or to a rock containing large crystals of one or more kinds of mineral embedded in a stone or glass matrix (prophyry). These differences

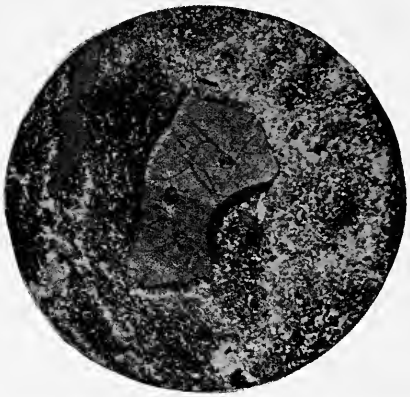


Fig. 14.—Microscopic appearance of porphyry.

Fig. 15.—Microscopic appearance of granite.

in the structure of rocks of the same composition will give rise to different soils. Glassy rocks will produce more or less homogenous particles, while crystalline rocks will weather into particles of different kinds, perhaps composed of the different minerals.

The chemical classification of igneous rocks depends on the relative quantities of silica and bases present. Since silica is the acid portion of minerals, rocks containing 65 to 75 per cent. of silica are termed acid rocks, those containing 55 to 65 per cent. are called intermediate, and those carrying 40 to 55 per cent. are called basic. Crystalline acid rocks contain quartz, while basic rocks do not contain enough silica for free quartz to crystallize out.

The *granite* group comprises rocks rich in silica and alkalies, containing 65 to 75 per cent. silica and 5 to 8 per cent. of alkalies, of which ¼ to ⅔ consists of potash. They are, as a rule, much richer in potash than other igneous rocks, and form correspondingly better soils.

Granite, the crystalline rock of this group, is very abundant, and soils derived from it are quite common. Granite soils are usually clay containing particles of quartz and mica, and they are often fertile, being especially rich in potash. Rhyolite, which is a porphyritic rock of this group, is extensively distributed in the western part of the United States.

The *syenite* group of rocks resembles the granite group, except that the rocks contain less silica (55 to 65 per cent.) and more bases to correspond. Like the granites, the syenites are rich in potash.

The *diorite* group contains about the same amount of silica as the syenites, but less alkalies and more lime and magnesia.

The *basalt* group contains the basic rocks (40 to 55 per cent. silica). These rocks contain small amounts of alkalies, and are rich in iron, lime, and magnesia.

The soils of the Piedmont plateau, in the eastern part of the United States, are derived mostly from igneous or metamorphic rocks, and consist of sands and clays containing quartz and mica. This area extends from New York City to near the middle of Alabama. The soils of the eastern Appalachian Mountain region are also of similar origin. An extensive area in Washington, Oregon, and Montana is covered with soils derived from the weathering of basalt and other igneous rocks.

Alluvial Soils.—The water falling on the ground and running off on its surface, carries soil particles with it. Streams or rivers take up particles of rocks or soil materials and carry them along. In time of flood, when both the volume and velocity of the stream are increased, this burden becomes much greater, since the carry-

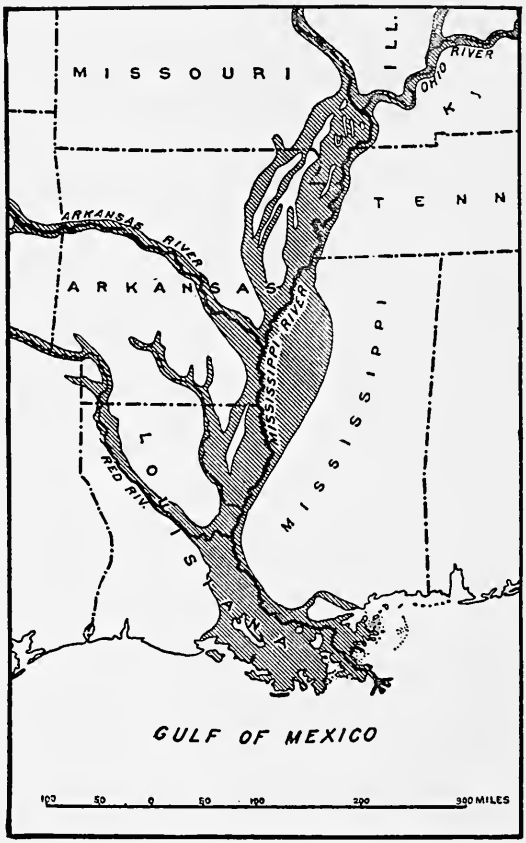


Fig. 16.—Sketch map showing the flood plain of the lower Mississippi. U. S. D. A.

ing power of water increases with the sixth power of the velocity with which it moves. That is, a river moving at the rate of four miles an hour may carry particles sixty-four times as

heavy as a river moving at the rate of two miles an hour. While being carried, the particles are ground together and reduced in size.

Whenever the velocity of a stream is decreased, it deposits a portion of its burden, the heavier particles being deposited first. Thus, when a swollen mountain stream issues from a gorge and spreads out over a plain, it deposits a portion of the material on the surface of the plain. When a river in flood leaves its banks, the velocity of the water is checked on spreading over the plain, and it deposits the coarser particles which it carries near the channel of the river. The finer particles are carried farther, and are deposited in the swamps or low ground at some distance from the river. The tendency of a river bearing rock debris is to build its banks up above the level of the surrounding country. The area over which a river spreads when in flood, is termed its *flood plain,* and the soil formed from the particles which it deposits is termed an *alluvial soil.* Some of the richest soils in the world are alluvial soils. The soils are deep, and as they receive the surface soil washed away from less fortunate regions from time to time, their fertility is maintained. The valleys of the Nile, of the Ganges, the Mississippi, the Red river, the Brazos, and others, contain some very rich soils, which are alluvial in origin. The soils near the river are lighter in texture than those in the low grounds back from the river. The latter are very heavy, and difficult to work, but are often very productive.

River deposits are stratified; that is, the material is sorted and deposited in layers consisting of material of very nearly the same fineness. Layers of fine and coarse material may alternate according to river conditions.

In arid regions, where the streams decrease as they flow from the mountains out upon the dry lowlands and are therefore compelled to lay aside a large portion of their burden, mountain streams may form wide-spread alluvial plains, which are called *piedmont* (meaning foot of the mountain) alluvial plains. The streams which flow eastward from the Rocky Mountains have formed a continuous alluvial plain which stretches hundreds of

miles from the base of the mountains, the deposits being in places five hundred feet thick. These deposits are now being eroded and reworked by streams.

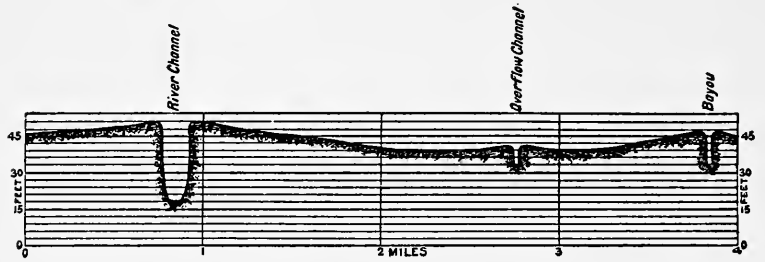


Fig. 17.—Profile showing how a river builds up its banks near the channel. U. S. D. A.

Alluvial soils, especially if deposited by large rivers, are derived from a mixture of minerals from different sources. The soils are more or less generalized and are usually very productive. Alluvial soils are found near rivers in all sections of the country. The most extensive alluvial soils are those near the Mississippi River and its tributaries, especially the Red River, the Arkansas, and the Missouri.

Fig. 18.—Alluvial cones, Wyoming.

Glacial Soils.—A glacier is a river of ice. It carries upon its surface and within its mass, soil and rock fragments derived from

the hills and cliffs which it passes. This material consists of all grades of particles, from fine fragments to large pieces of rock. The rock fragments are usually angular, and some of them may be marked with parallel scratches. These scratches are caused by a rock held in the moving ice and pressing against another rock in the earth's crust.

Fig. 19.—Unstratified glacial drift near Chicago.

At the end of the glacier is deposited a mixture of earth and rocks of all sizes, which is known as a *moraine*. When the coming of a higher yearly temperature causes the front of a glacier to retreat, it leaves the surface of the earth covered with the mixed deposit characteristic of glaciers. The deposit beneath the glacier, which is called *till,* is sometimes an extremely dense, stony clay, having been compacted under the pressure of the moving ice.

The northern part of the United States was once covered by a great glacier sheet, stretching down from Canada. Glacial soils are accordingly found in New York, Ohio, and other Northern States. Some of these deposits have been reworked by rivers until their glacial characteristics are no longer easily recognized. Glacial soils are especially important in New York and states north of it, and in the states north of the Ohio and Missouri rivers. They frequently contain considerable amounts of carbonate of lime.

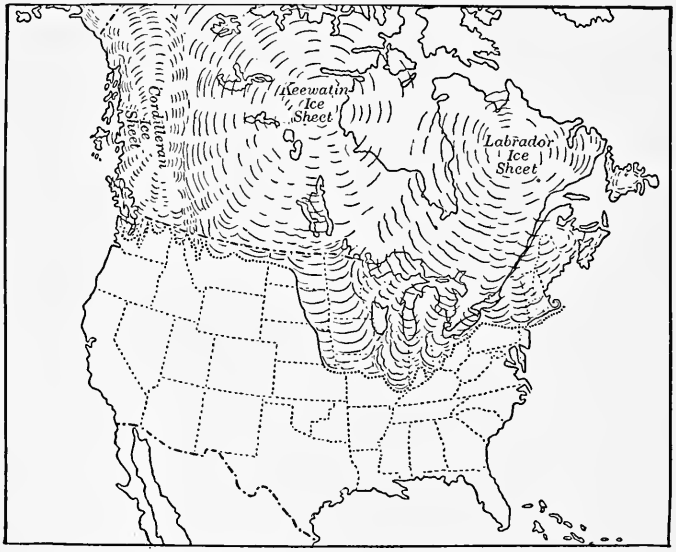


Fig. 20.—Hypothetical map of glacial sheets of North America. Salisbury.

The waters from the melting of the glacial sheet also carried ground-up material. Though this was sorted by the water, it is different from ordinary alluvial soils. These soils are found in the area adjacent to the glacial regions.

Loess, finely ground material derived from glacial drift and transported by winds or flowing water, consists of grains of quartz, feldspar, mica, hornblende, with some limestone and clay.

Wind Blown Soils.—In any region where the soil becomes very dry and is not covered with vegetation, as in deserts or arid sections, the soil particles may be taken up by wind, and perhaps carried considerable distances. The attrition of the wind-borne particles reduces the softer minerals rapidly to dust, and harder minerals, such as quartz, more slowly. The dust and sand are separated, as the dust is carried farther. Wind-borne desert sands thus consist largely of quartz. Dust carried by upward-whirling winds into the higher currents of the air, is often transported for hundreds of miles beyond the arid region from which it is taken. In 1901 dust carried from the Sahara northward by a storm, fell with rain over southern and central Europe and as far north as central Germany and Denmark, causing a "black rain."

Fig. 21.—Dune sands, Lake Michigan.

In northern China an area as large as France is deeply covered with a yellow pulverulent earth called *loess*, but which many consider a dust deposit blown from the great Mongolian desert to the west of it. The soils of some of our western States are wind-blown soils.

Even in humid climates, in many places along the seashore, or lake beaches, as in New Jersey or Michigan, the beach sand is

heaped by the wind into wave-like hills called dunes. Dunes whose sands are not fixed by vegetation, travel slowly with the wind, and they may invade and destroy forests and fields, and bury villages beneath their slowly advancing waves. River deposits on flood plains are often worked over by the winds during summer droughts, and much of the silt is caught and held by the forests and grassy fields bordering on the area.

Wind-blown materials may aid in the formation of soils even in humid regions. Thus, Hall[1] relates that a beach composed of coarse rocks (shingle) was found in years to have accumulated a few inches of a black powder, probably borne there by the wind.

Soils from Oceanic Deposits.—The more important oceanic deposits from which soils are derived are sands and sandstones,

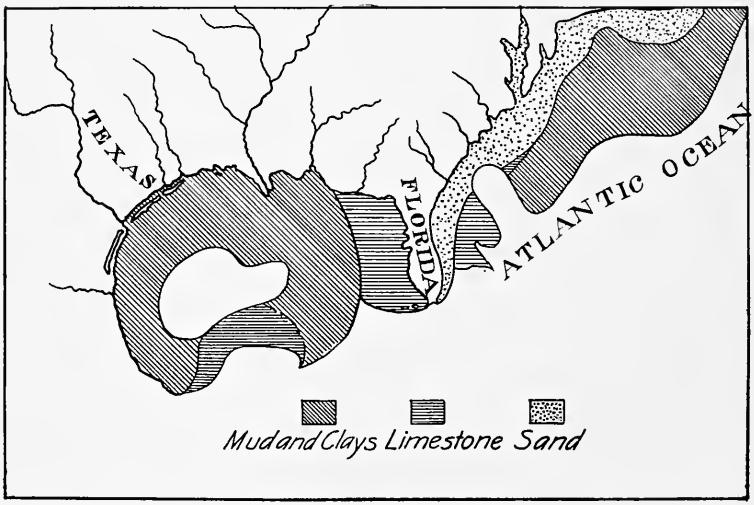


Fig. 22.—Present distribution of deposits in the Atlantic near the United States.

muds, shales, and other consolidated sediments, and limestone deposits. The material of the oceanic deposits comes from the wear and tear of the waves on the shore, and from the waste

[1] The Soil, p. 10.

brought down by rivers. It is estimated that the waste derived from cliffs, etc., along the seashore is about three per cent. of that brought down by rivers.

Sands are deposited along the shores of the sea. Boulders, pebbles, and coarse sand, are deposited in order near in shore, and the finer sands farther out. Beach sand derived from rocks of neighboring cliffs or brought down by torrential rains from mountain regions is dark, and contains grains of many minerals other than quartz. These sands contain more plant food and make richer soils than sands from low-lying shores. The white sand of low shore beaches, such as those on the east coast of the United States from Virginia to Florida, consists almost entirely of quartz grains. The other and softer minerals have been entirely beaten to mud and deposited farther out during the long period that the material has been exposed to the waves. These sands are poor in plant food, but they are excellent soils for some purposes.

Sandstone consists of sand grains cemented together by silica, carbonate of lime, or oxide of iron. Such deposits are widely distributed, and many soils are derived from them. The quality of the soil depends largely upon the origin of the sands. Quartz is sandstone, which, by the action of heat and pressure, has been metamorphosed in the crust of the earth.

Muds are deposited beyond the sand deposits, and also in quiet water near shore, and in river deltas. Muds contain the finer particles from the wear of rocks. The soils derived from them contain more plant food than sands and produce longer, but are not adapted to the same kinds of plants.

Muds may be consolidated into mudstone or shales or metamorphosed by heat and pressure into schists and slates. Soils are formed by the weathering of all these deposits.

Limestone deposits are formed from the shells of molluscs, and deposits of coral, and other marine organisms which secrete carbonate of lime from solution in the sea-water, some of which are minute in size. These deposits are usually formed in the shallow water beyond the area in which mud is deposited; they also make

up a large part of the deep sea deposit. Phosphoric acid is fixed in small quantities in these deposits.

Limestone deposits may be metamorphosed into limestone rock, marble, or other crystalline forms of lime. By the weathering of such deposits, many fertile soils have been formed. Some old soils of limestone origin are practically free of carbonate of lime, and are very poor.

Deposits in Lakes.—Lakes are not permanent, geologically, but are gradually filled with deposits of waste brought into them by rivers, unless the lake is drained before such filling takes place. The lake is first converted into a swamp, and finally into dry land.

In lakes without an outlet, various salts are deposited. Such lakes can exist only in dry climates, where the loss by evaporation is equal to or greater than the amount of water brought in by rivers. Rivers carry with them not only visible waste, consisting of particles of rock in suspension, but also invisible waste, or material in solution, which consists of carbonate of lime, sulphate of lime, chloride of soda or common salt, etc. This waste accumulates in lakes having no outlet. Deposits of gypsum (sulphate of lime), salt, carbonate of lime, and other salts, are left when such lakes dry up. The carbonate of lime is first deposited, then gypsum. As the liquid becomes more concentrated, common salt is deposited, next sulphate of magnesia, then potash salts, and chloride of magnesia. The deposition may be checked by influx of water at any stage, the deposits already made being perhaps covered with mud, and a new series of deposits started on top of these. The German potash salts are supposed to be of such origin.

Peat and Muck Soils.—When a soil is saturated with water, vegetation does not decay as rapidly as in a drained soil, but accumulates, forming a peat or muck soil. Peat soils are also formed in cool and damp climates, by the growth of a moss, which is able to hold water tenaciously.

Soil Provinces of the United States.—The Bureau of Soils[1] of the U. S. Department of Agriculture divides the United States

[1] Bulletin No. 55.

into thirteen provinces, based chiefly on climate, origin and topography of the soils. These are better shown in the map than described. Two great divisions are based on climate; first, humid, and second, arid and semi-arid. The soil provinces are as follows:

Humid Division.—1. *Atlantic and Gulf Coastal Plains.*—These consist of a belt of land narrow in New Jersey but much wider towards the south. The surface is a plain cut into hills and valleys by rivers, about 200 to 300 feet above sea level along the inner margin, but nearer the coast it has many areas with deficient drainage. The soils are made up of gravels, sands, and sandy clays. The deposits on the Atlantic coast are derived from the Piedmont Plateau through oceanic agencies, while the deposits on the gulf coast are derived from material transported from glacial deposits and from the western plains. There are also some soils derived from limestone deposits.

Fig. 23.—Shell rock, Florida.

2. *Piedmont Plateau.*—This area lies between the coastal plain and the Appalachian Mountains, and is most extensive in Virginia, North Carolina, South Carolina, and Georgia. The altitude varies from 300 to over 1,000 feet above sea level. These soils are derived largely from the weathering of igneous and metamorphic rocks in place. The prevailing series of these soils are the Cecil series and the Chester series. Both these series usually contain mica and quartz.

3. *Appalachian Mountains and Allegheny Plateau.*—The soils of the eastern ranges of these mountains are of igneous or metamorphic origin, while the western ranges and the Allegheny plateau are of sedimentary origin. General farming is not practiced in a large part of this area on account of the unevenness of its topography. The land is, however, well suited to grazing and fruit growing.

4. *Limestone Valleys and Uplands.*—These occur in narrow valleys among the Appalachian mountains and plateaus near by, and in two large areas, one in central Kentucky and Tennessee, the other in Missouri and northern Arkansas. The limestone soils are derived from the weathering of limestone, and many of them contain but a small percentage of the original limestone rock. Each foot of the soil is the residue from the weathering of many feet of the rock.

5. *Glacial and Loessial Deposits.*—This area covers a large portion of the United States, especially in the north-central states. A large portion of this area was covered by a great continental glacier, which in its southern movement filled up valleys, plowed off hills and mountains, and deposited the ground-up material varying from a few feet to over 30 feet in thickness. The soils are partly till, or heavy clay compacted under the glacier, but largely "loess," a fine silty deposit containing limestone and very fertile. Some of the material was brought long distances, but most of it is composed of ground-up underlying rock largely deposited from glacial streams.

6. *Glacial Lake and River Terraces.*—These are deposits formed by the Great Lakes, after the close of the glacial period, when they were much larger than they are now. Several terraces marked by the old shore line can be observed. The soils vary from beach gravels to off-shore deposits of heavy clays, and the material worked over by the water is partly of sedimentary and partly of igneous origin.

7. *River Flood Plains.*—These soils are most extensive along the Mississippi and its tributaries, and along rivers in Texas and Louisiana, though soils of this group are found in all areas. The

deposits derived from various kinds of materials has been laid down by the river when in flood. Such soils are usually fertile, though they may not always be profitably cropped.

Arid and Semi-Arid Division.—8. *Great Basin.*—The soils are derived from a great variety of rocks and consist of colluvial soils of the mountain slopes, lake and shore deposits, stream valley sediments, and river-delta deposits.

9. *Arid Southwest.*—These soils occupy slopes at the foot of mountains, alluvial plains, sloping or nearly level plains, and

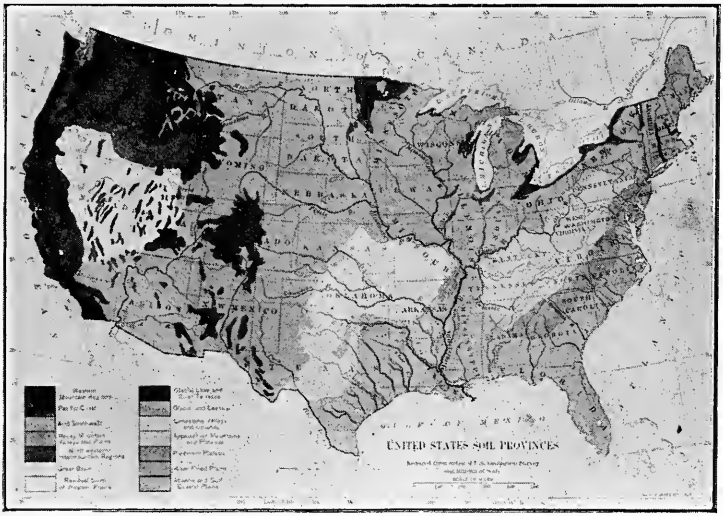


Fig. 24.—Soil provinces of the United States. Bureau of Soils.

stream valleys. The soils are colluvial, alluvial, and lake deposits. Without irrigation, these soils have little agricultural value.

10. *Residual Soils of the Western Prairie Regions.*—These soils occupy the unglaciated part of the prairie plains. The rocks from which the soils are derived are of the carboniferous age and consist of sandstones, shales, and limestones.

11. *Northwestern Inter-Mountain Region.*—The soils of this area consist mostly of residual material derived from basaltic

lava and in some cases granitic rocks. Some are derived from ancient lake beds.

12. *Rocky Mountain Valleys, Plateaus and Plains.*—These soils are derived from a great variety of igneous, metamorphic, and sedimentary rocks. The soils of the mountain slopes are usually of little agricultural value, while those of the plateaus, valleys, and plains range from grazing land of low value to soils adapted to fruit, sugar beets, and other special crops.

13. *Pacific Coast.*—Soils found in this region range from residual and colluvial soils of the mountain sides, foot slopes and foot hills, to deep and extensive river flood plains and delta sediments, and ancient and modern shore and lake deposits. Their value depends largely upon possibilities of irrigation, and local conditions of rainfall and temperature.

CHAPTER V.

PHYSICAL COMPOSITION AND CLASSES OF SOILS.

Soils are composed of particles of different sizes, ranging from over 2 mm. to 0.0001 mm. or less, in diameter. Many of the physical properties of soils are closely related to the relative abundance of particles of different sizes. The surface area of a cubic foot of the particles increases with their fineness of division. The retentive power for moisture, the area exposed for chemical action and for the feeding of roots, the capillary action of the soil, etc., are closely related to the size of the soil particles.

Soil particles may be found independent of one another, but they are usually more or less united into crumbs, compound particles, or lumps.

Mechanical Analysis.—By the mechanical analysis of a soil, we mean the estimation of the relative quantities of soil particles of different sizes. As the particles which make up the soil have almost an infinite variety of size, all that can be done is to group them, by placing all that are between certain dimensions in a certain group. The sizes selected for the groups, and the name given to each, are purely arbitrary. A number of systems of soil analysis is possible. The principal groupings of soil particles in mechanical analysis used in the United States are those of Hilgard, and, those of the Bureau of Soils. Other systems are used abroad. The Bureau of Soils makes seven separations. Dr. E. W. Hilgard has made a number of analyses based on the velocity of a current of water holding the particles in suspension, stated in millimeters per second (hydraulic value). For example, sand of 0.5 to 0.30 mm. in diameter is held in suspension by a current of water moving at the rate of 64 millimeters per second.

There has been little or no work to determine the classification of soil particles which would best correlate the properties of the soil with the physical analysis. So far as the writer has been able to find, the division into groups is arbitrary.

The following table compares the systems of Hilgard and of the Bureau of Soils:

Bureau of Soils		Hilgard		
Name	Sizes of particles MM.	Sizes of particles MM.	Hydraulic Value	Name
Stones, sticks, etc..	Over 2			
Fine gravel.....	2–1	3–1	—	Grit
Coarse sand	1–0.5	1–0.5	—	
Medium sand.....	0.5–0.25	0.5–0.3	64	
		0.3–0.16	32	Sand
Fine sand	0.25–0.1	0.16–0.12	16	
		0.12–0.72	8	
Very fine sand.....	0.1–0.05	0.072–0.047	4	
Silt	0.05–0.005	0.047–0.036	2	
		0.036–0.025	1	Silt
		0.025–0.016	0 5	
		0.016–0.010	0.25	
Clay		0.010– ?		Clay

It is possible, by combining some of the groups of Hilgard, to compare the results with analyses of the Bureau of Soils. As Hilgard[1] remarks, a subdivision of six or seven classes, as is made by the Bureau of Soils, is sufficient for a great many cases. There is, however, considerable difference in the properties of the grades of silt which are separated by Hilgard but grouped together by the Bureau of Soils.

Methods of Analysis.—For the separation of the finer particles, all methods of mechanical analysis take advantage of the different rates of subsidence of particles of different diameters when suspended in water. Methods such as that of Osborne depend upon subsidence under the influence of gravity in stationary columns of water. Hilgard's method depends upon the difference between the action of gravity and the carrying power of a current of water. The Bureau of Soils throws down all except the clay particles by centrifugal force. Sieves are used for separation of the coarser particles; compound particles are broken down by shaking with water, or boiling. Since clay is liable to form compound particles, and otherwise interfere with the separations, it is removed first.

[1] The Soil.

Method of the Bureau of Soils.[1]—The following is an outline of the method of mechanical analysis of soils used by the Bureau of Soils. Five grams of soil are shaken for six hours or longer

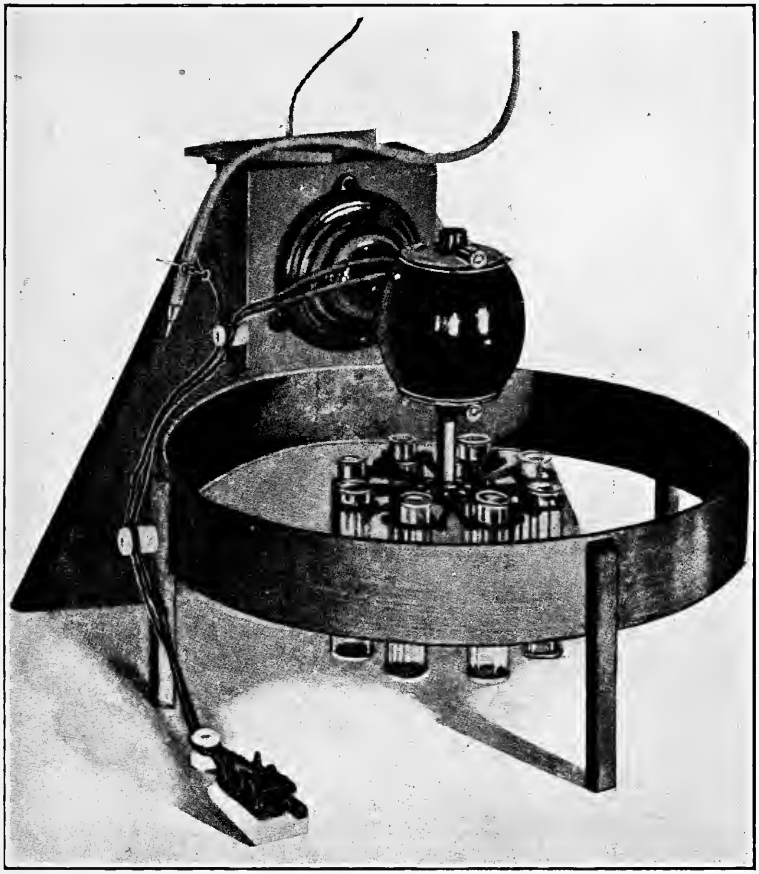


Fig. 25.—Centrifugal machine used in mechanical analysis of soils.

with water containing a little ammonia, in order to decompose the compound particles. The soil is then washed into a centrifugal tube, and the centrifugal machine run at full speed for about

[1] Bulletin 24, and Bulletin 84.

three minutes, the time depending on the speed of the machine and the quantity of suspended material present. The material in suspension is then examined with a microscope carrying a micrometer eye-piece, to see if any particles larger than clay (.005 mm. in diameter) remain in suspension. If larger particles are found, the centrifugal is run until they settle. When the water contains only clay particles, it is decanted. The residue is stirred up with water, the machine started, and the separation made as before. The operation is repeated until the clay has been all removed, as shown by a microscopic examination of the residue. The water is evaporated to dryness, and the clay weighed.

The residue left in the tubes is brought in suspension with water, and allowed to settle, until microscopic examination shows only silt in suspension. This requires but a short time. The silt water is decanted, and the operation repeated until all the silt (less than .05 mm. in diameter) has been washed out. The silt, after being allowed to settle, is collected, dried and weighed. The sand is then collected, dried, and separated into five groups by means of a nest of four sieves, two of brass with circular perforations 1 mm. and 0.5 mm. in diameter, and two of silk bolting cloth with openings 0.25 and 0.1 mm. wide. The various separations are then weighed.

Hilgard's Method.—The following is an outline of Hilgard's method. (For full details see Wiley's "Agricultural Analysis.") The two grades of grit are removed by sieves. Ten or 15 grams of the sifted soil are boiled with water to break up the compound particles, transferred to a beaker, mixed with water, and allowed to stand a short time until only the finest silt and clay remain in suspension. The treatment with water is repeated until the water has removed all the finest silt and clay. The mixture of clay and silt-water is allowed to stand 24 to 60 hours, until all silt is deposited. The sediment is rubbed with a rubber pestle, mixed with water, and allowed to settle again until free from clay. It is then dried and weighed. An aliquot of the clay-water may be evaporated to dryness and the residue weighed, or the clay may be precipitated by coagulation with salt.

The mixed sediments, containing the sand and all the silt except the finest, is placed in an upright glass cylinder, containing a rotating fan or churn, run by a suitable motor. This breaks up the compound particles. A current of water is run in so that it moves through the cylinder at the rate of 0.25 mm. per second, until the water becomes clear. The particles carried over are allowed to settle, dried and weighed. The current of water is increased to 0.5 mm. per second, so as to remove another grade

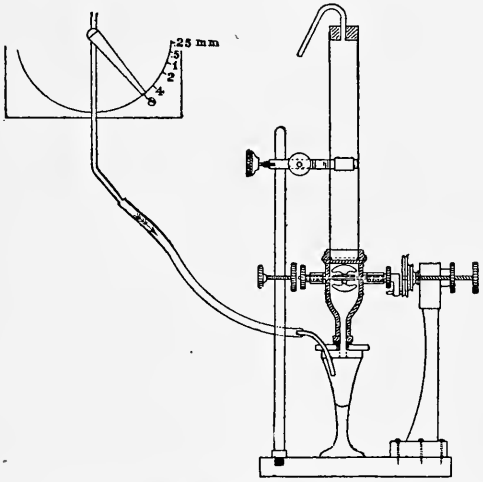


Fig. 26.—Hilgard's apparatus for mechanical analysis by means of a current of water.

of particles, and these operations are repeated until all the grades of particles are separated.

Relation of Grain Size to Soil Texture.—This relation is studied by ascertaining the mechanical analysis of soils of known properties, and also by investigating the properties of the various groups of particles separated in the analysis.

In *sands* the coarser particles of the soil predominate. Such soils are open or porous, easy to cultivate, not very retentive of moisture, and warm up early in the spring. Coarse sands are least retentive of moisture and most porous. Soils containing quantities of very fine sand are much more retentive of moisture.

In heavy *clay* soils, the fine clay particles are present in large quantity. Such soils are very retentive of moisture, require much labor in cultivation, are likely to be tough and sticky when not ploughed at exactly the right time, are not easily penetrated

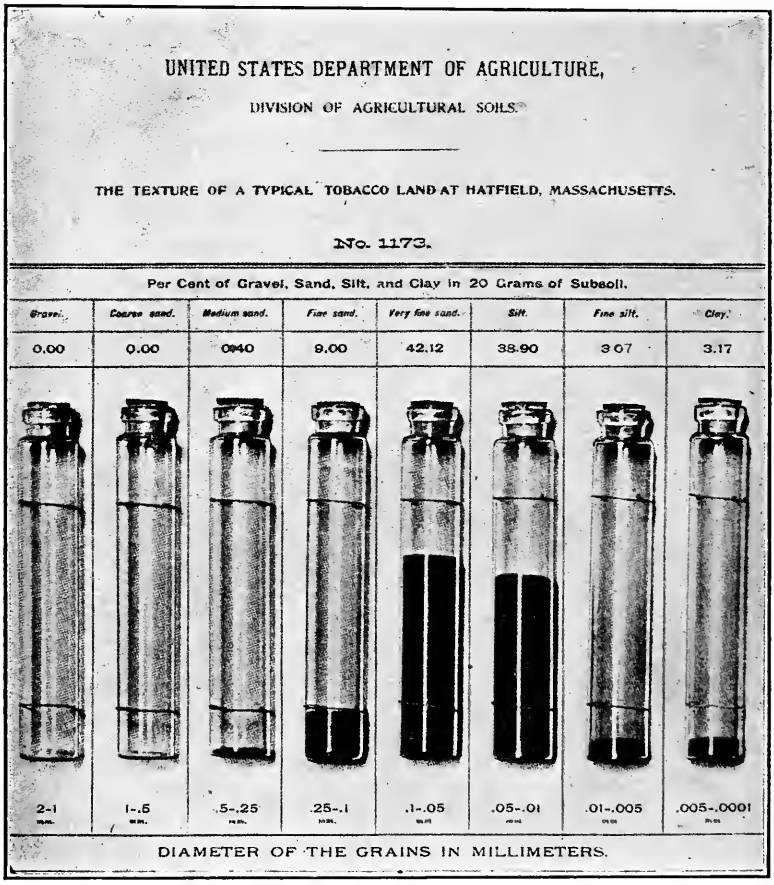


Fig. 27.—Physical analysis of a soil sample. Bureau of Soils.

by water, and do not warm up rapidly in the spring. Twenty per cent. clay particles usually make a soil difficult to work.

Soils with much silt and little or no clay, are likely to adhere

to the plow very tenaciously when too wet. They plough fairly well when in right condition, but turn up in clods if ploughed when dry. Loams are intermediate between sands and clays, in physical character and in properties, and in general are good soils.

The coarse soil particles, therefore, tend to make the soil more open and porous and more easily tilled. The fine particles tend to make the soil more compact and less easily tilled. The final resultant depends upon the relative quantities of the different kinds of particles, as well as their chemical composition or their properties. The presence of a certain amount of clay in a sand is desirable. If no clay is present, the soil is liable to pack on wetting, but clay holds the particles into crumbs characteristic of a well tilled soil. Further, sands containing less than 4 per cent. clay have little power of retaining moisture and are particularly liable to suffer from drought Sand particles in a clay will not diminish its stickiness, while silt particles make the clay less adhesive, though perhaps more heavy to work.

Mechanical analysis is also to be interpreted with consideration as to the amount and distribution of rainfall and the temperature and the effect of the underground water. A light soil under heavy rainfall may behave like a heavier soil under light rainfall. A soil with ground-water at such distance that it may be brought to the roots of plants by capillary action, is in better condition than when the ground-water is deeper.

Classes of Soil Related to Mechanical Analysis.—Soils are classed as sands, loams, clays, etc., according to their physical characteristics. There is room for difference of opinion as to exactly what characteristics should be signified by each term. The classification is made partly by field observations, and partly by mechanical analysis.

As a result of the mechanical analysis of a great number of soils, the Bureau of Soils[1] of the U. S. Department of Agriculture finds different types to have the following average composition (see table).

The predominance of various grades of material is well brought out in the table. For example, the coarse sands contain on an

[1] Bulletin No. 78.

average 31 per cent. coarse sand particles, the sands 37 per cent. of fine sand particles, the fine sands 57 per cent. fine sand particles. The clays contain 42 per cent. clay particles.

AVERAGE COMPOSITION OF SOIL TYPES AS ANALYZED IN CONNECTION WITH THE SOIL SURVEYS.

Soil classes	Number of samples	Fine gravel	Coarse sand	Medium sand	Fine sand	Very fine sand	Silt	Clay
		Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
Coarse sands	135	12	31	19	20	6	7	5
Sands	401	2	15	23	37	11	7	5
Fine sands	511	1	4	10	57	17	7	4
Sandy loams	1,141	4	13	12	25	13	21	12
Fine sandy loams	934	1	3	4	32	24	24	12
Loams	659	2	5	5	15	17	40	16
Silt loams	1,268	1	2	1	5	11	65	15
Sandy clays	162	2	8	8	30	12	13	27
Clay loams	718	1	4	4	14	13	38	26
Silty clay loams	765	—	2	1	4	7	61	25
Clay	1,970	1	3	2	8	8	36	42

The classification of soils with regard to physical composition, as used by the Bureau of Soils,[1] is shown in the following table. The classification is controlled by field observations.

CLASSIFICATION OF SOIL MATERIALS.

Soils containing —20 silt and clay:

- Coarse sand — 25+ fine gravel and coarse sand, and less than 50 any other grade.
- Sand — 25+ fine gravel, coarse and medium sand, and less than 50 fine sand.
- Fine sand — 50+ fine sand, or —25 fine gravel, coarse and medium sand, 50+ very fine sand.
- Very fine sand — 50+ very fine sand.

Soils containing 20–50 silt and clay:

- Sandy loam — 25+ fine gravel, coarse and medium sand.
- Fine sandy loam — 50+ fine sand, or —25 fine gravel, coarse and medium sand.
- Sandy clay — 20 silt.

Soils containing 50+ silt and clay:

- Loam — 20 clay, —50 silt.
- Silt loam — 20 clay, 50+ silt.
- Clay loam — 20–30 clay, —50 silt.
- Silty clay loam — 20–30 clay, 50+ silt.
- Clay — 30+ clay.

[1] Bulletin No. 78.

The figures given represent per cent.; the minus sign (—) represents, less, and the plus sign (+) represents more; and the sign (-) when used between two figures, thus 20-50, gives limiting values, and should be read from 20 per cent. to 50 per cent. Thus, 25 + means 25 per cent. or more; — 25 means less than 25 per cent.

For example, a soil containing less than 20 per cent. silt and clay and over 50 per cent fine sand, would be called a fine sand. A soil containing over 50 per cent. silt and clay particles and over 30 per cent. clay would be called a clay soil.

Relation of Chemical Composition to Soil Texture.—The effect of the physical composition of a soil is modified by the chemical character of its constituents. The three important modifying constituents are organic matter, colloidal clay, and carbonate of lime.

Organic matter binds a loose soil, and lightens a heavy soil, and thus reduces the difference between them. When there is a large quantity of organic matter, the mechanical analysis loses much of its significance.

Carbonate of lime (1 to 2 per cent.) also lightens a clay soil and otherwise modifies its properties. For example,[1] the following pairs of soils had similar physical composition but differed decidedly in properties:

	Per cent. carbonate lime	
	Holsey green	Rothamsted
(a) Too sticky to be cultivated	0.48	0.16
(b) Heavy soil, but works well	1.02	3.0

It is very well known that calcareous clay soils are more easily cultivated and break up better than similar soils deficient in lime.

The clay particles, so called, may be composed of quartz dust, hydrated oxide of iron, gelatinous silica, carbonate of lime, hydrated silicates, and of true clay, or hydrated silicate of alumina. These substances have different properties, and the

[1] Hall, Jour. Agr. Sci., 1911, p. 187.

composition of the clay particles undoubtedly influences the character of the soil. The term "Klay" has been proposed to distinguish the clay particles of a soil from the hydrated aluminium silicate termed clay by the chemist.

True clay is present in the soil in two forms. First, as colloidal clay in a swelled condition; and second, as clay in non-colloid, or shrunken condition. In the colloid condition, clay remains suspended in water indefinitely. Small amounts of lime and other substances coagulate the clay and cause it to separate out in flakes. When the coagulating substance is removed, the clay again becomes colloidal. This may be easily shown by washing a clay soil with acid to remove lime, then with water, and shaking it with ammonia. Clay will enter into suspension and remain suspended a long time, but if ammonium sulphate, ammonium carbonate, or other salts are added, the clay quickly separates in flakes.

Colloidal clay was prepared by Schloesing.[1] He brought the clay into suspension in water, as in the mechanical analysis of a soil, and precipitated the clay with a small quantity of acid, collected the colloidal clay on a filter, and washed with distilled water. The residue on the filter was treated with ammonia, and diffused in a considerable quantity of distilled water. This was then left until deposition ceased, which required several months. The microscope could then no longer detect particles of visible dimensions in the solution. The liquid was decanted off, and the colloidal clay precipitated by the addition of a small quantity of acid. It dried to a translucent, horn-like mass. According to Schloesing, even the stiffest natural clays seldom contain more than 1.5 per cent. of such true colloidal clay.

Colloidal clay has much higher binding properties than shrunken or coagulated clay. The tenacity of a soil containing colloidal clay is greatly influenced by its condition. If the clay is in its fully swelled condition, the soil exhibits its maximum cohesion, and if a sufficient quantity of clay is present, it will be quite impervious to water. If the colloidal clay is in a shrunken coagulated state,

[1] Chimie Agricole, 1885.

the same soil may be pervious to water and susceptible of successful tillage.

Boiling in water, freezing, working the wet soil, alcohol, ether, sodium or potassium hydroxides, ammonia, and sodium or potassium carbonates, cause the clay to swell and increase its colloidal properties. These agencies, therefore, tend to make clay soils more impervious, sticky, and difficult to work. Lime, magnesia, bicarbonate of lime, certain acids, such as hydrochloric or sulphuric, and certain salts such as sodium chloride, sodium sulphate, calcium sulphate, coagulate the clay particles. These substances, therefore, tend to make clay soils less sticky and more permeable to water.

If clay is washed and kneaded when wet, it becomes plastic and sticky, and may be moulded into forms which retain their shape and become hard and stony when dried and baked. Advantage is taken of this property in the manufacture of brick, earthenware, and chinaware, but it is not a desirable property in a soil.

Hydrated oxide of iron, and some of the other bodies which occur in the clay separation do not have the binding properties of true clay, and if present to any considerable extent, the soil may not have the characteristics which would be expected from the quantity of clay in it. Hilgard,[1] for example, finds that a certain clay soil containing 40 per cent. of clay was scarcely as adhesive as another soil containing 25 per cent. of clay, and not nearly as sticky when wet as a third soil containing 33 per cent. clay. The soil first named, however, was rich in ferric hydrate, a large portion of which is probably in the clay particles. This accounts for the behavior of the soil. Ferric oxide appears to diminish the tenacity of a clay.

Rivers which contain little lime are turbid from presence of clay, but 70 to 80 mg. lime per liter precipitates the clay and leaves the water clear.

Calcareous clays are very sticky when wet, but many of them disintegrate into a mass of crumbs on drying, thereby producing

[1] The Soil, p. 100.

good tilth, even though worked when wet. Non-calcareous clays under such conditions are likely to contract into stony masses. The exact proportions of carbonate of lime necessary to produce this condition of the soil remains to be determined.

The black prairie soil of Texas locally called "black waxy" and termed the "Houston black clay" by the Bureau of Soils, is an example of this kind of soil. When wet it is gummy and waxy, but when dry and well cultivated it is friable and easily worked. This soil contains one per cent or more of lime. Clay, unlike silt, chalk, and humus, increases greatly in coherence when it dries, and finally becomes a hard, solid substance.

Nature of Tilth.[1]—If the particles of a soil are each independent of the other, so that their relative positions are easily shifted by gravity or water, they are said to possess the single-grain structure. Such soils, if sandy, are loose, and become as compact as their particles allow. Clay soils of this character are very sticky when wet, and if worked while wet form clods on drying.

A soil which, when plowed, breaks up into a mass of compound particles of various sizes, loosely piled upon one another and separated by comparatively large interspaces, is said to possess the *crumb* structure and to be in *good tilth*. The crumbs may be held together by moisture, clay, humates, carbonate of lime, and sometimes silica and oxide of iron.

Crumbs of sand held together by water collapse on drying. Clay is frequently the substance which holds the crumbs together; in such case, the crumb structure remains even after the land dries out. Beating rains and cultivation while too wet destroy these crumbs.

Soil particles united by carbonate of lime, humates, silica, or oxide of iron are more or less permanently cemented into compound particles. In some calcareous soils we find sandy and silt concretions varying from several inches in size to microscopic proportions. Humus is a great aid in securing good tilth.

Compound particles are also formed by natural processes, due

[1] Warington, Physical Properties of Soil, p. 36.

to changes in temperature, or to changes in moisture content. If the soil is beaten or mixed when too wet, compound particles are destroyed and the soil dries into a hard compact mass.

Tilth is a condition of the soil, and only indirectly due to processes of tillage. A heavy soil is not reduced to powder by the mechanical force exerted through implements. Tillage stirs the soil, and places it so that natural forces exert their greatest effect upon it. The soil in good tilth falls into a powder under the action of the various instruments. Such a condition of the soil is very desirable. It allows the preparation of a good seed bed; it is most suitable for ensuring the best conditions of moisture, temperature, and chemical action in the soil during the growth of the plant. The maintenance of good tilth is especially important on clay soils.

The production of a good tilth, and the permeability of a clay soil to water, depend largely upon the formation and maintenance of compound particles. The conditions favorable to the formation of compound particles are also favorable to the coagulation of clay. Any change which converts the clay from a coagulated to a swelled condition is necessarily destructive to compound particles, but it is quite possible to destroy compound particles without affecting the coagulated condition of the clay.

Relation of Physical Composition to Adaptation of Crops.—The adaptation of different crops to particular kinds of soil is due to different needs of the crops for moisture, for soil atmosphere, for temperature, and their habits of root growth. The differences in physical composition cause soils to respond differently to these needs, and hence vary their adaptation. But climatic conditions of rainfall, temperature and situation, modify the way which the soil fulfills these conditions. Under similar conditions, and in a general way, there is a relation between the physical character of the soil and its adaptation to crops, and this is shown by the general agricultural practice and treatment of such soils.

The relation of physical character to adaptation to crops is studied by ascertaining the kinds of crops actually grown upon the various classes of soils, and how well they thrive on them.

The relation between physical character and adaptation in the soils of the Atlantic and Gulf Coastal Plains, as ascertained by field agents of the Bureau of Soils,[1] is as follows:

Sands.—These soils are characterized by open structure, thorough drainage and warm nature. They are the earliest truck soils, produce light yields, and are not well adapted for general farming.

Fine Sands.—These are more retentive of moisture than the sands, mature truck ten days to two weeks later, and give heavier yields. They are not well adapted for general farming.

Sandy Loam Soils.—These are the medium early truck and light general farming soils of the Atlantic and Gulf Coastal Plains. They are the lightest desirable soils for general farming, are more retentive of moisture than the fine sands, and mature crops about two weeks later. In general farming, crop returns are light.

Fine Sandy Loams.—These soils are adapted to medium truck crops, give moderately good yields of vegetables, and give average yields of general farm crops. Cotton matures somewhat later than on the sandy soil.

Loams.—These soils produce medium-late truck crops and are the best soils for general farming in this region. They are easily kept in good condition of tilth and are very retentive of moisture. Vegetables mature late but the yields are good. Small grains and grasses do well.

Silt Loams.—These are adapted to late truck, vegetables for canning purposes and for heavy farm crops or for special purposes. Hay does well on this type of soil.

Clay Loams.—These are too stiff and too late in maturing crops for vegetables. A small number of farm crops is adapted to this type. Wheat, oats, rice, forage crops, and grass do well.

Clays.—These are adapted to heavy farm crops, such as wheat, grass, rice, and forage crops for ensilage. Cultivation is difficult. Early varieties of cotton do well outside of boll weevil districts.

A specific example of the relation between the use made of

[1] Bulletin No. 78.

a soil and its physical analysis, is shown by the analyses of typical Maryland subsoils published by Whitney.[1]

PHYSICAL ANALYSES OF MARYLAND SUBSOILS.

	Diameter of particles	Early market garden	Market garden	Tobacco land	Wheat soil	Wheat and grass	Grass and wheat
Fine gravel	2-1.0	0.5	0.4	1.5	—	—	1.3
Coarse sand....	1.0-0.05	5.0	2.0	5.7	0.4	0.2	0.3
Medium sand ..	0.5-0.25	40.2	28.6	13.3	0.6	1.3	1.1
Fine sand.....	0.25-0.10	27.6	39.7	8.4	22.6	4.0	1.0
Very fine sand .	0.10-0.05	12.1	11.4	15.0	30.6	11.6	6.9
Silt	0.05-0.01	7.7	5.0	28.9	14.0	39.0	29.1
Fine silt	0.01-0.005	2.2	2.0	7.8	4.1	8.8	11.0
Clay.....	0.005-	4.4	8.8	14.6	22.0	32.7	43.4

The early market garden soil contains nearly 73 per cent. sand. It has little power of retaining water and is therefore warm and dry. It produces vegetables about ten days earlier than any other soil in Maryland.

The market garden soil contains more fine sand and more clay. It is more productive but later in maturing spring crops than the soil named above. It is superior to the first soil for peaches, small fruit, and autumn crops.

The tobacco soils contain 10 to 20 per cent. clay, the lighter soil yielding a smaller crop but a better quality of leaf. The wheat soils are somewhat heavier. The wheat soil (No. 4) is the lightest soil upon which wheat can profitably be grown in Maryland. The soil is too light for permanent meadow or pasture and too heavy for the best quality of tobacco. The wheat and grass land is more productive than the wheat soil. The grass and wheat soil is still more productive.

Similar relations can be traced for other soils, between the physical composition and crops adapted to them. Other factors come into play, however, such as the location of the soil, its depth, and its chemical composition. The physical properties of a soil depend upon other things in addition to its physical composition, as we shall see. The relation between soil composition and crop adaptation probably depends to a large extent upon

[1] U. S. Weather Bureau, Bulletin No. 4.

water conditions, which is largely influenced by the physical composition of the soil.

Similar relations between physical character and crop adaptation were traced in England by Hall.[1] He found very heavy soils generally used for pasture. Wheat soils are heavy. Barley soils are lighter than wheat soils, potato soils are still lighter. Hop soils are somewhat like barley soils. Fruit soils are lighter than hop soils. The different kinds of fruit have their own requirements. Waste soils are characterized by large amounts of coarse sand, small amounts of clay and fine silt, an acid reaction and absence of calcium carbonate.

Analyses of typical soils used for various crops in the area studied by Hall are shown in the table. The reader will notice that the groups of soil particles are different from those elsewhere mentioned in this chapter.

	Wheat	Barley	Potatoes	Hops	Fruits
Fine gravel above 1 mm.	1.4	1.2	0.9	1.2	1.0
Coarse sand 1-0.2 " .	3.7	18.3	20.1	4.8	6.8
Fine sand 0.2-0.04 " .	24.5	32.0	43.5	33.8	42.0
Silt 0.04-0.01 " .	23.0	18.2	11.0	28.3	23.3
Fine silt 0.01-0.002 " .	12.8	8.0	6.4	8.7	7.3
Clay below 0.002 " .	20.8	11.9	9.7	12.1	10.9

The subsoil is generally heavier in texture, or contains more clay, than the surface soil. This is largely due to the action of water moving the finer particles of the soil into its lower portions.

Soil Types and Soil Series.—A *soil type* is a definite soil, with a definite physical composition and other definite properties. It may vary somewhat in different parts of the area, but in all essential respects, it is the same soil.

Soil series are groups of soil types related to one another through source of material, method of formation, topographic position, coloration, and other characteristics. The soil types in the series vary chiefly in physical composition and other characteristics caused thereby. A soil series, to be complete, would

[1] Jour. Agr. Sci., 1911, p. 206.

contain all the possible physical classes of soils already mentioned. Comparatively few soil series, however, are complete.

In establishing soil types and soil series, the texture of the soil, its mechanical composition, its origin, the topography of the soil, native vegetation, color, depth, drainage, and all other factors which influence the relation of the soil to the crop, are considered, as far as possible. Both the surface soil, and the subsoil should be considered. All the types in a given locality have been formed by the same general processes, and will naturally grade into one another. In humid regions, the description of a type covers the material to an average depth of three feet; in arid regions to a depth of six feet. Minor variations of texture, structure, organic matter content, or succession of materials, which occur in sections representing 10 acres or less, are described as phases by the field agents of the Bureau of Soils. There is some local variation in types. Differences in agricultural value may be due to differences in treatment of the same soil.

The soil name of a type does not mean that it belongs to that class necessarily. For example, Norfolk sandy loam may be a coarse to medium yellow or gray *sand* or light *sandy loam.*

Fippin[1] suggests the following scheme of soil classification. The broadest division is based on temperature, into (I) temperate, (II) subtropical, (III) tropical regions. Each of these is sub-divided into (A) humid, (B) semi-arid, (C) arid sections based on rainfall. The next two sub-divisions are into divisions and provinces according to mode of formation; (*a*) sedentary, soils sub-divided into (a_1) residual soils and (a_2) cumulose soils and (*b*) transported soils, sub-divided into (b_1) colluvial, (b_2) wind borne, (b_3) transported by water; namely, (b_{3a}) ocean, (b_{3b}) lakes, (b_{3c}) rivers. The soils of different origin are next divided into groups based on the source of material (1) acid and basic igneous rock; (2) shale and slate; (3) sandstone and quartzite; (4) limestone and marble rock; (5) muck, peat, and swamps (cumulose soil). The next sub-division is into series, based on color, organic matter, drainage, lime content, and special

[1] Proc. Am. Soc. Agron., 1911, p. 88.

chemical properties. Finally, the types, or individual soils, are based on texture and structure. This scheme offers good possibilities; the group, acid and basic igneous rocks, is, however, a broad one and should be sub-divided.

Some Soil Series.—Soil types numbering 715 have been established by the Bureau of Soils of the United States Department of Agriculture. These types have been divided into 86 series. A full list and description of these types and series is found in Bulletins 55 and 78 of the Bureau mentioned. The following are a few series, mentioned for the sake of illustration.

Atlantic and Gulf Coastal Plains.—*Houston Series.*—Dark-gray or black calcareous prairies. One of the most productive series for upland cotton, and well adapted to alfalfa and other forage crops.

Norfolk Series.—Light-colored soils with yellow sand or sandy clay subsoils. This series contains some of the most valuable truck soils of the Atlantic and Gulf Coast States, and certain members of the series are adapted under certain climatic conditions to wheat, grass, tobacco, and fruit.

Orangeburg Series.—Light-colored soils with red sandy clay subsoils. This series constitutes some of the best cotton soils of the South, and certain members of the series are particularly adapted to tobacco.

Portsmouth Series.—Dark-colored soils with yellow or mottled gray sand or sandy clay subsoils. Where drainage is adequate, this series is adapted to some of the heavier crops, to small fruits, and to Indian corn.

Susquehanna Series.—Gray soils with heavy red clay subsoils which become mottled and variegated in color in the deep subsoil. Only one member of the series, the sandy loam, has been developed to any considerable extent. This one is used for fruit and general farm purposes, but the other members are particularly refractory and difficult to bring into a productive state.

River Flood Plain.—*Miller Series.*—Brown to red alluvial soils formed from the reworking of materials derived from the Permian Red Beds. Very productive soils, suitable for cotton,

corn, sugar-cane, alfalfa, and vegetables; especially adapted to peaches.

Wabash Series.—Dark-brown or black soils subject to overflow. Very productive soils, used for cotton, sugar-cane, corn, wheat, oats, grass, alfalfa, sugar beets, potatoes, and other vegetables.

Piedmont Plateau.—*Cecil Series.*—Gray to red soils with bright-red clay subsoils, derived from igneous and metamorphic rocks. Constituting by far the larger portion of the plateau, these soils are well adapted to and are used for cotton, export tobacco, and fruit, and the lighter members for truck crops. As a rule they are not highly developed, but where properly handled, the heavier members produce excellent crops of corn and grazing and hay grasses.

Appalachian Mountains and Plateau.—*Dekalb Series.*—Brown to yellow soils with yellow subsoils, derived from sandstones and shales. Soils of this series are used, according to texture, elevation, exposure, and character of surface, either for the production of hay, for pasture, or for orchard and small fruit.

Porters Series.—Gray to red soils with red clay subsoils, derived from igneous and metamorphic rocks. This is the most important series for mountain fruits of the eastern United States. It is also used for general farming.

Limestone Valleys and Uplands.—*Clarksville Series.*—Light-gray to brown soils with yellow to red subsoils, derived mainly from the St. Louis limestone. Apples and peaches are commercially important. Tobacco is a leading product.

Cumberland Series.—Brown surface soils, derived from the deposit of sedimentary material overlying residual limestone subsoils. Used for cotton and other general farm crops, truck, and fruit.

Glacial and Loessial Regions.—*Marshall Series.*—Dark-colored upland prairie soils. The principal soils of the great corn belt belong to this series, while in the Northwest the finest wheat soils are found in this group. They are among the best general farming soils of the entire country.

Miami Series.—Light-colored upland timbered soils. The different members of this series are considered good general farming soils and have in addition special adaptations for truck, small fruit, and alfalfa.

Glacial, Lake and River Terraces.—*Clyde Series.*—Dark-colored swamp soils formed from reworked glacial material deposited in glacial lakes. A special use for these soils is the production of sugar beets, while general farm crops, truck, and canning crops are grown extensively.

Fargo Series.—Black calcareous soils rich in organic matter formed by deposition of material in glacial lakes. This is the most important group of soils in the Red River Valley, and includes exceptional soils for the production of wheat, barley, and flax.

Residual Soils of the Western Prairie Region.—*Crawford Series.*—Brown soils with reddish subsoils, derived from limestones. The soils of this series range from rough areas suited mainly for pastures to fertile general farming, fruit-growing, and trucking soils.

Great Basin.—*Bingham Series.*—Porous dark or drab colluvial and alluvial soils underlaid by gravel or rock, occupying lower mountain slopes. The lighter types, when irrigable, are devoted to orchard fruits, and the heavier types, to alfalfa and sugar beets.

Northwestern Intermountain Region.—*Bridger Series.*—Dark-colored soils with sticky yellow subsoils, of colluvial and alluvial origin. These soils generally occupy elevated foot slopes or sloping valley plains and have not been developed to a great extent. They are most extensively used for the production of grain, and when irrigated, are utilized in the production of alfalfa and other hay crops; under favorable climatic conditions they are adapted to fruits.

Rocky Mountain Valleys, Plateaus, and Plains.—*Billings Series.*—Compact adobe-like gray to dark or brown soils and subsoils, formed mainly by reworking of sandstones and shales and occupying old elevated stream terraces. This is an important series adapted to alfalfa and general farm crops and stock raising;

also used to a considerable extent in the production of sugar beets.

Arid Southwest.—*Gila Series.*—Light to dark brown soils of flood-plain alluvium underlaid at varying depths by coarse sands and gravels. Under favorable irrigation and drainage conditions, the members of the Gila series are adapted chiefly to the production of alfalfa, potatoes, truck, and root crops.

Pacific Coast.—*Fresno Series.*—Light-colored soils with light-gray, ashy subsoils and alkali-carbonate hardpan, derived from old alluvial wash. Where protected from alkali accumulations, these soils have been very successfully used for vineyards and raisin grapes, and are particularly adapted to almonds, peaches, and apricots.

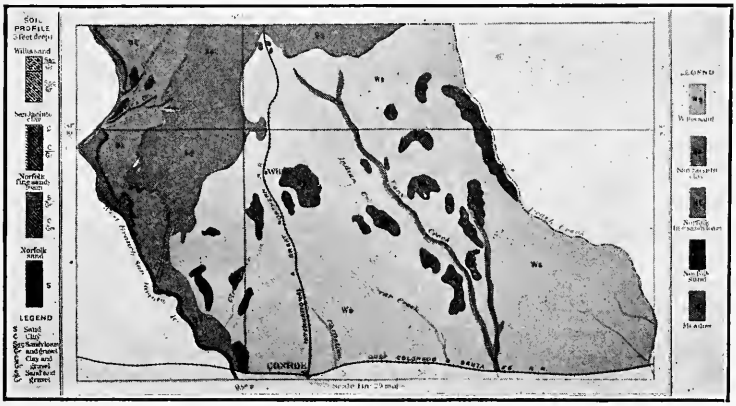


Fig. 28.—Photograph of a soil map, Willis area, Texas.

Soil Survey.—The soil surveyor is provided with a map, compass, measuring instruments, and soil sampler. After a general inspection has been made, and the provisional types decided upon, the mapping is begun. Preliminary borings in the soil are made to outline the location of a body of soil of uniform character. This is then colored in on the map. The surveyor then works away from this area until a different type of soil is encountered.

The line of separation between these two types (which may consist of a narrow strip of intermediate soil) is then outlined on the map. Other areas are outlined in the same manner.

The identification of the types is aided by physical analysis. It is, of course, not possible to make a great number of types in a given area, and a certain latitude must be allowed, between which limits the soil may vary. As a rule the different types of soil and their properties are very well known to the farmers in the area surveyed. So far the types have been largely based upon physical differences as observed by the surveyor, with no great emphasis on the physical analysis.

Value of Soil Survey.—A soil survey outlines the various types of soil in the area surveyed, shows their extent and relative importance, and exhibits, to some extent, the soil problems of the locality. It also indicates the adaptation of the various types of soil to different crops.

A soil survey should not be considered as an end in itself, but as a means of ascertaining the various types of soil in the area, as a basis for further study. Thorough chemical, physical, bacteriological, and other studies should then be made of the various types of soils. The results of these studies can then be applied to definite areas.

Soil surveys also show what crops may possibly be grown upon the various types of soil in question. Information secured upon the same types in other districts, may be made available. Results of fertilizer experiments made upon definite types of soil can be applied to similar types of soils elsewhere, but not indiscriminately, as has been too often done. Other experimental work can also be definitely applied to the kind of soil on which it is carried out. Relations between the various types should be traced so that work on one type may be applied to other types.

CHAPTER VI.

PHYSICAL PROPERTIES OF SOILS.

The soil affects the growth of the plant through both physical and chemical properties, which react upon, and modify one another. The chief physical conditions which affect the plant are the depth of the soil, its temperature, the amount of water it supplies, and the composition of the soil atmosphere. These are modified by a variety of factors. The chief chemical condition which affects plants is the supply of plant food, but this supply is to some extent dependent upon physical factors. The chemical composition of the soil has other effects upon plants. It affects the physical character of the soil. It is related to the condition of the soil as regards neutrality, and the absence or presence of injurious substances, which also modify the relation of soil to plants.

The physical and chemical properties of the soil are closely related, and are more or less dependent upon one another. They cannot be entirely separated without presenting a very one-sided view of the functions of the soil.

Soil and Subsoil.—Going down into the soil from the surface, we generally find the following layers: First, the top, or surface soil, varying from 3 inches to a foot or more in depth, and usually darker in color than the layers below. Next is the subsoil, from a few inches to several feet in depth. If the soil is sedentary, below this is a mixture of rock fragments and soil, and then comes the rock of the locality, the upper layers of which are decomposed and rotten. Sometimes the layer of soil rests directly upon the solid rock. Sometimes the surface soil has been washed away, leaving the unproductive subsoil.

The surface soil is distinguished from the subsoil by its darker color, due to the decaying vegetable matter contained in it, derived from roots and plant residues. The depth of the surface soil is, in humid climates, often determined by the depth of plowing, and is generally from 4 to 12 inches.

A different definition of soil and subsoil is used by the Bureau

of Soils. The surface soil is the upper layer of the earth, and continues until there is a decided change in physical character. In other words, the distinction between soil and subsoil is based upon differences in mechanical composition.

In humid sections, the subsoil is not well suited for the growth of plants. If it is exposed by removal of the surface soil, it is in most cases unproductive until it has been subjected to atmospheric influences for some time. Organic matter added to the soil, such as manure, is said to aid in converting the raw subsoil into productive soil. If too much subsoil is mixed with the surface soil, by deep plowing, the productiveness of the soil may be decreased. In arid regions, according to Hilgard,[1] the soil is suitable for plants to the depth of three to ten feet, or more. Material from the depth of eight feet has been put on gardens and served well the first year. In preparing land for irrigation, the land is leveled without regard to the subsoil, and no bad effects are noticed. These practices would be injurious to humid soils. The difference is due to the greater depth of penetration of air and the roots of plants, under arid conditions.

Penetration of Roots.—The depth to which roots penetrate into the soil depends upon the condition of the soil and subsoil, the climate, and the kind of plant. The roots of plants grown in humid regions penetrate only a comparatively short distance. In arid climates it is necessary that the roots penetrate deeply, in order that they may endure drought.

According to Hilgard, the roots of the hop have been found, in arid climates, to penetrate to the depth of 18 feet; roots of wheat and barley may reach to 4 to 7 feet in sandy soil; roots of grape vines have been found at the depth of 22 feet below the surface. Thus in arid climates, where a drought of five or six months prevails during the growing season, the roots of plants, by penetrating to considerable distances, will secure water in the depths of the soil. The depth to which plants send their roots affects the quantity both of water and of plant food at their disposal. Differences in the needs of plants for food may, in part, be due to

[1] The Soil, p. 163.

differences in rooting habits. Further, the character of root growth is also related to the kind of tillage which should be given. Crops whose roots extend near the surface of the soil should not have these roots cut by deep cultivation.

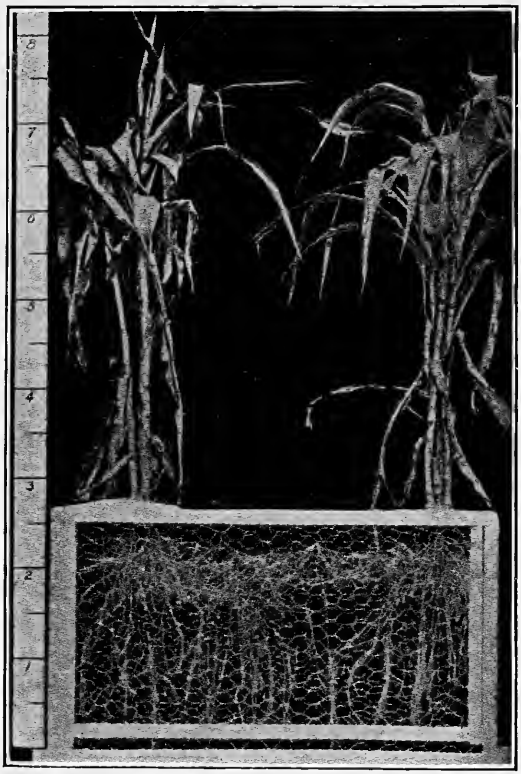


Fig. 29.—Distribution of roots of corn, Kansas.

Exhibition specimens of roots are secured in the following manner.[1] A block of soil is cut out, with the plant in the center, and a wooden frame covered with one-half inch mesh wire netting is slipped over it. Plaster of Paris paste is then poured on the top to hold the plant and large numbers of sharpened wires are pushed through the soil and fastened to the netting, to hold the

[1] Kansas Bulletins 75, 127; North Dakota Bulletin 43, 64.

roots in place. When the plaster hardens the dirt is washed away by a stream of water.

Sanborn[1] drove an iron frame into the soil, removed the soil in layers of one inch to the depth of a foot, and washed out the roots. The roots were dried and weighed in order to ascertain their distribution in the soil layers.

At the Arkansas Experiment Station,[2] plants were grown in boxes 10 by 12 inches and 4 feet deep, and the quantity of roots in different layers of the soil was determined. These conditions are somewhat artificial, and the roots would probably penetrate deeper than in a natural soil.

The results of the preceding experiments are summarized in the following table:

Barley	96 per cent. of roots in first 7 inches (Utah)
Corn	90 " " " 7 "
Corn	93 " " " 7 "
Clover 4 years old	94 " " " 7 "
Clover	Evenly distributed between the first 2 feet (Arkansas).
Millet	80 per cent. in the first 12 inches (Arkansas)
Oats	96 " " 7 " (Utah)
Orchard grass	90 " " 20 " (Arkansas)
Peas	Mostly in 12 to 18 inches of soil "
Potatoes	70 per cent. in 7th to 13th inch (Utah)
Timothy	87 " in first 7 inches (Utah)
Timothy	95 " " 6 " (Arkansas)
Wheat	92 " " 7 " (Utah)

It appears that barley, corn, oats, timothy, and wheat developed over 86 per cent. of their roots in the first seven inches of soil. Most of the plant food and water which they take up must necessarily be drawn from this layer. Clover, millet, peas, orchard grass, and potatoes appear to send their roots deeper, but these results (with the exception of the potatoes) are from the Arkansas Station, where the plants were grown in boxes and not in the free soil. Plants grown in boxes, as in the Arkansas Experiment, would have a tendency to send their roots deeper than plants grown in the natural soil, on account of the pulveriza-

[1] Utah Experiment Station, Bulletin 32.

[2] Bulletin 29.

tion and exposure to the atmosphere that the soil received in filling the boxes, and also because the boxes were probably underdrained.

Other experiments made at the Kansas, New York, North Dakota, Iowa, and Minnesota Stations, show that the greatest proportion of the roots of plants develop in the surface foot of the soil, but appreciable quantities of roots may penetrate much deeper. These experiments were qualitative. Further quantitative experiments are needed, as it is very important for scientific soil studies, to know the quantitative distribution of the roots of various plants in various soil types and in various sections of the country.

The depth to which roots of some plants may penetrate is shown in the following table, taken from experiments made in Kansas and North Dakota. The subsoil was in some cases a stiff, clay soil.

DEPTH OF PENETRATION OF ROOTS OF PLANTS.

Alfalfa	6 to 10 feet.	Clover	2½ feet.
Corn	2½ to 6 "	Cowpeas	3 "
Grasses	2½ to 3 "	Kaffir corn	3½ to 5 "
Millet	2 to 3 "	Milo maize	3½ to 4 "
Oats	4 "	Potatoes	3 "
Rye	3 "	Sorghum	3½ to 4 "
Sugar beet	3½ to 4 "	Wheat	4 "

Effect of Depth of Soil on Plants.—The depth to which the roots of plants penetrate depends both upon the character of the soil and the habit of the plant. The roots of plants can penetrate easily in a sandy subsoil, but may have difficulty in entering heavy clay.

In general, the deeper the roots can penetrate the soil, the better the growth of the crop. Roots which occupy 12 inches of soil will have twice as much soil to draw upon for moisture and for plant food, as those which occupy only 6 inches. They will also have twice as much space in which to expand their roots.

The experiments of Lemmerman[1] may be cited as showing the effect of root space upon plant growth. He grew mustard in pots of the same surface area, but of different depths. One vessel of

[1] Jahresber. f. Agr. Chem., 1903, p. 42.

each size received no fertilizer, and one of each size received 1, 2, and 3 grams fertilizer respectively. The results are as follows:

WEIGHT OF CROP IN DIFFERENT SIZED VESSELS.

Fertilizer	Large vessel	Small vessel
	Grams	Grams
0	26.8	19.7
1	40.5	36.2
2	61.1	47.8
3	62.1	48.3

The increase of fertilizer from 2 to 3 grams had little effect upon the crop in the pots of either size. That is, the limiting condition is the size of the pot. The crop in the large pot is considerably larger than in the small one; this shows that the space occupied by the roots has considerable influence. However, this difference may be due to differences in moisture content.

Limitations of Soil Depth.—The depth of the surface soil, as stated, is largely dependent upon the depth of plowing. The surface and subsoil together may be so shallow as to interfere seriously with the productiveness of the soil. The limiting condition may be hard pan, the water table, rock, or heavy subsoil.

Hard pan is a layer of hard earth, sometimes rock-like, which cannot be penetrated by plant roots. Hard pan may be caused by constant plowing at the same depth. The sole of the plow consolidates the layer of soil on which it slips. Such hard pan is most liable to occur in heavy clay soils. Hard pan may also be caused by deposition of matter from drainage or irrigation waters. The deposited matter cements the soil grains into rocky masses. The cement is usually carbonate of lime, but sometimes it is an iron cement, or a humate.

Hard pan may be prevented by varying the depth of plowing, or by an occasional subsoiling. It is particularly liable to occur in arid climates. In some localities it should be destroyed with dynamite or other explosives before fruit trees are set out.

Rock, when too near the surface, forbids the use of the soil for

cultivated crops, though the land may possibly be used for timber or grazing.

The water table, when too near the surface, converts the soil into a swamp. When somewhat lower, the soil is suitable for some plants, but is too wet for agricultural purposes. If from 4 to 6 feet below the surface, the soil is suitable for cultivation, but the water table is often considerably lower than this.

In *arid climates* a proper substratum is much more important than in humid climates, since the roots must be able to penetrate deeply in order to endure drought. Hilgard[1] gives the following examples of faulty substrata found in California.

A. The surface soil of about 12 inches is underlaid by horizontal layers of shale. This soil might possibly be rendered useful by blasting with explosive.

B. The surface soil of 12 inches is underlaid by a heavy red clay, which can hardly be penetrated by roots. After blasting with dynamite this soil has been used successfully. Without blasting, orchards die in about three years.

C. This soil has a calcareous hard pan at the depth of about four feet. On account of the arid climate, the roots of trees must be able to penetrate to a greater depth than this.

D. The water level is about three feet. This prevents root penetration and restricts the use of the soil to shallow rooted crops. This condition may arise from the leakage of water from irrigation ditches.

E. The soil is underlaid by a layer of coarse sand or gravel at the depth of about four feet, through which roots will not penetrate to the water below. A large number of orchards have died from this cause.

Soil Temperature.—Processes of plant and animal life can go on only between certain limits of temperature. The temperature to which the plant is subject depends upon both the soil and atmospheric conditions, the latter being perhaps the controlling factor.

[1] The Soil, p. 177.

The earlier the soil warms up in the spring, the earlier it can be planted. Some few seeds begin to germinate at the freezing

Fig. 30.—Fruit grown against a wall so that it will ripen. France.

point, but most seeds require a higher temperature. Haberlandt[1]

[1] Landw. Versuchs-stat., 17, p. 104.

tested various seeds at several temperatures and found the lowest temperature at which germination took place was as follows:

Alfalfa, beets, barley, beans, red clover, oats, peas, turnips, wheat.. 32-40° F.
Indian corn, carrots, sorghum, sunflower, timothy ..... 40–51° F.
Cucumbers, melons ..... 60–65° F.

The time required for germination decreases as the temperature rises, until the optimum temperature is reached. For example, corn required 11¼ days to germinate at 50°, 3¼ days at 60°, and 3 days at 65° F. While the sunflower seeds required 25 days at 51°, at 60° they required only 3 days to germinate.

The growth of the plant also depends upon the temperature to which it is subjected. Between the extremes of heat and cold fatal to plants, is an optimum temperature, varying for different plants, at which the maximum growth takes place. For example, Bialablocki[1] grew rye, barley, and wheat 20 days at different soil temperatures, and determined the dry matter produced, with the following results:

WEIGHT OF PLANTS GROWN AT DIFFERENT TEMPERATURES.

Temperature	Rye	Barley	Wheat
Degrees	Mg.	Mg.	Mg.
8	23.9	17.1	15.8
10	20.8	18.0	20.8
15	32.4	34.4	29.5
20	49 5	36.7	30.8
25	42.4	42.0	43.9
30	47.0	35.0	46.9
40	31.2	26.3	40.3

In this experiment, 20° was the most favorable temperature for rye, 25° for barley, and 30° for wheat. The wheat plant grown at 30° is three times as large as that at 8° C.

The temperature of the soil has a direct influence not only upon the plant, but upon processes in the soil, especially those relative to the preparation of soil nitrogen for plant food.

Factors which Influence Soil Temperature.—The temperature of the soil varies to a certain extent with that of the air, but the

[1] Jahresber f. Agr. Chem., 1870-72, p. 190.

changes are slower and more restricted in depth. The temperature of the soil is influenced by its color, water content, location, composition, etc.

Location.—The following figure illustrates the effect of location upon the light and heat received by the soil from the sun. Let E and F. represent two equal beams of sunlight, falling upon the south (A B) and the north (C D) side of a hill. It is evident

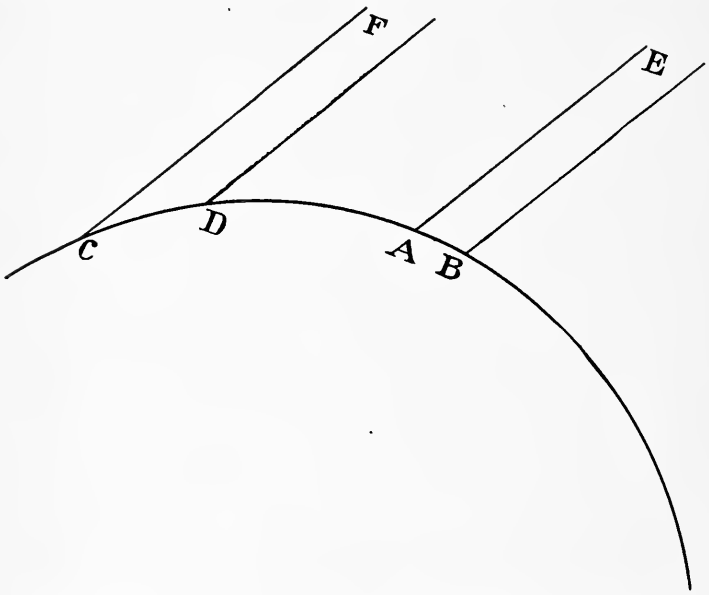


Fig. 31.—The south side of a hill receives more heat than the north.

that the ray F is distributed over more surface than the ray E and that its heat has a greater area to warm. The soil on the north side thus receives less heat than that on the south side. The difference depends on the situation of the sun, and the inclination of the hill. It is for this reason that the south sides of hills in northern regions may be green with vegetation while the north side is covered with snow. A wall or hedge, by protecting the soil from wind, or by reflecting heat upon it, may cause the soil to be warmer. Maligoti and Durocher found the average soil

temperature on the south of a garden wall 8° C., higher than on the north side. In cool climates, fruits which refuse to ripen under ordinary conditions may attain perfection when trained against the sunny side of a wall.

Water Content.—The quantity of heat required to raise the temperature of the soil depends upon the materials of which it is composed, but it increases with the quantity of water present. Approximately five times as much heat is required to raise the temperature of one pound of water one degree as for one pound of soil. Since wet soil does not warm up as rapidly as a dry soil, draining a wet soil makes it warmer, as a general rule. Clay soils, since they contain more water, do not warm up as quickly as sandy soils, which retain much less water. This is probably the reason sandy soils are so much better suited to early truck crops than are clay soils. They warm up quicker, and maintain a higher temperature during the early part of the year, thereby forcing the growth of the crop.

The evaporation of water from wet soils also makes them colder than dry soils, as water in passing into the form of a vapor takes up considerable amounts of heat. King found that a clay soil was 4° to 7° F. lower in temperature than a sandy soil.

Color.—The color of the soil has an effect upon its temperature. A dark soil warms up more rapidly than a light one, provided they contain an equal quantity of water and other conditions are equal. Schubler exposed two layers of the same soil to the sun under the same conditions, making one white by means of a thin layer of magnesia, and the other black with lampblack. The temperature of the blackened soil became 13° to 14° higher than that of the whitened one. Lampadius has given the soil a coating of coal dust an inch thick to aid in ripening melons, and in Belgium and Germany it is found that the grape matures best on certain soils covered with gray slate. These fragments, however, retain the heat through the night. Black soils often contain more water than light soils, and the light soils therefore warm up first.

Organic matter, in decaying, gives off heat. This heat is

utilized in preparing hot beds with manure and earth. The decay of the manure raises the temperature of the hot bed.

The quantity of organic matter in the soil is seldom sufficient to affect its temperature to a practical extent. An application of 10 tons of partly decayed manure per acre may raise the temperature of the soil 2° F. for the first five days, 1°F. for the second five days, and 0.6° F. the third. This is according to the experiments of Georgeson.[1] This increase in temperature might aid in hastening the germination of seeds and in protecting a spring crop from frost.

Wagner found an average increase of temperature 0.7 to 0.2° F. during four to twelve weeks, due to heavy applications of manure under field conditions.

Control of Temperature.—Artificial regulation of temperature is practiced comparatively little in agriculture, though of considerable importance in horticulture, in which hot beds, cold frames, and green houses are used. The growth of tomato plants, sweet potato vines, and other plants under glass or in protected places, for transplanting when the soil becomes sufficiently warm or danger of frost is past, is a kind of regulation of temperature. In some regions, smoke fogs are produced to prevent frost and thereby protect tender plants, or plants at critical stages of growth.

Color of Soils.—Soils range in color from almost pure white, through yellow, red, or gray, to black. The yellow or red colors are due usually to hydrated oxides of iron. Organic matter gives a soil a black color when wet, or a gray or brown or black color when dry. The color thus affords some indication as to the character of the soil. Black or red soils are generally preferred by practical farmers. The intensity of the color is not always an indication as to the quantity of organic matter or oxide of iron present. A coarse sand, by having a smaller surface to be colored, requires much less coloring material than a clay soil which has a large surface.

[1] Agr. Science 1, p. 251.

Specific Gravity of Soils.—The specific gravity of a body is the weight of the body divided by the weight of an equal volume of water. Suppose we place 10 grams of soil in a bottle of known weight which holds exactly 25 cubic centimeters, and weigh. Then fill the bottle exactly full of water, so that it contains no air, and weigh again. The gain in weight subtracted from the weight of 25 cubic centimeters of water gives the weight of water displaced by 10 grams soil. Ten divided by this gives the specific gravity of the soil.

In estimating the specific gravity of a body, we must allow for the space occupied by air. If the soil could be fused into a solid mass without chemical change, the weight of 1 cubic centimeter expressed in grams would be the specific gravity.

The specific gravity of some soil materials is given in the following table:

Specific Gravity of Soil Materials.

Quartz	2.6	Water	1.0
Felspar	2.5–2.8	Humus	1.2–1.5
Limestone	2.6–2.8	Mica	2.8–3.2
Granite	2.6–2.7	Hornblende	2.9–3.4
Clay	2.5	Talc	2.6–2.7

Specific Gravity of Soils.

Clay soil	2.65
Sandy soil	2.67
Fine soil	2.71
Humus soil	2.53

Apparent Specific Gravity.—The apparent specific gravity of a soil is the weight of a given volume of the soil, including air spaces, compared with the weight of an equal volume of water.

Apparent specific gravity depends upon the true specific gravity of the soil particles, and the amount of air spaces in the soil. The former is constant, the latter is variable, as it depends upon the size and shape of the soil particles and the treatment to which the soil has been subjected. A cultivated soil contains more air spaces than the same soil in pasture.

The apparent specific gravity will vary, then, with the treatment to which the soil has been subjected, if it is determined in

the field. In the laboratory the apparent specific gravity will vary with the method used for determining it.

The apparent specific gravity of a soil is determined by weighing the dry soil that occupies a given volume. In the field this is accomplished by driving a tube of definite size, not less than 2 inches in diameter, into the soil, so as to remove a core of known volume. The core is removed, dried and weighed, and the weight divided by the volume is the apparent density.

Apparent density is determined in the laboratory by packing 200 to 1000 cc. of the soil into a glass cylinder, and weighing it. This method to a certain extent is applicable to incoherent soils, but is not well suited to clay soils, in which the action of water has a decided effect upon the apparent density. It represents the weight of the soil when in condition of good tilth.

The apparent specific gravities of different kinds of soils are as follows, according to Schubler:[1]

	Apparent specific gravity	Weight of dry soil per cubic foot	Weight per acre to the depth of 1 foot in pounds
Sand	1.76	110 lbs.	4,790,000
Ordinary land	1.28	80–90 "	3,5-3,900,000
Heavy clay	1.20	75 "	3,270,000
Peat	0.48–0.80	30–50 "	1,3-2,180,000

Sandy soils, usually termed "light," are the heaviest of all, while clayey land, termed "heavy" weighs less than ordinary soils. The terms "light" and "heavy" refer to the readiness with which the soils are worked by the plow, light soils requiring much less labor than heavy ones.

The actual weight of the soil in the field varies with the quantity of water present. A peaty soil saturated with water is very heavy.

Since soil analyses are made by weight, differences in the apparent specific gravity of soils must be taken into consideration in interpreting the results.

[1] Stockbridge, Rocks and Soils, p. 153.

The apparent specific gravity of soils taken in the field appears to increase as we go downward. This is in part due to the pressure of the overlying stratum; in part to the action of rain carrying the finest particles of the soil into the open spaces of the subsoil; in part to the loosening action of tillage and plant and animal life on the surface soil and to the presence of their residues.

The weights of the soil per acre were studied[1] at Rothamsted and Woburn, England, by driving down an iron frame 6 inches square and 9 inches deep. The core of soil was removed, dried, and weighed.

Weight of Soil per Acre.

	Pasture Rothamsted	Arable land Rothamsted	Arable land Woburn
First 9 inches	2,300,000	2,900,000	3,200,000
Second 9 inches	3,100,000	3,000,000	3,400,000
Third 9 inches	3,300,000	3,200,000	3,500,000
Fourth 9 inches	3,300,000	3,300,000	3,500,000

The Rothamsted soil is a heavy loam or clay subsoil beneath which is the chalk. The Woburn soil is a light sand.

Air Space in Soils.—The quantity of air space in soils may be calculated from the apparent and the real specific gravity. To say that the soil has an apparent specific gravity of 1.20 means that 1 cc. of the loose soil weighs 1.20 grams. If the soil material has the real specific gravity of 2.5, then 1 cc. weighs 2.5 grams, and 1.20 grams of it occupies 1.20 divided by 2.50 equals 0.48 cc. Thus 0.52 cc. or 52 per cent., is air space in this particular instance.

Adhesion and Cohesion.—Cohesion is the force with which the soil particles adhere to one another. It varies with the amount of water present and the nature of the soil, from zero in some sands, to a high degree in some clays when dry. Soils with little cohesion when dry are liable to be blown by winds unless protected by vegetation. The larger the particles of soil, the less is

[1] Warington, Physical Properties of Soil, p. 46.

the cohesion between them. When the particles correspond in size to silt, the wet soil may be a sticky mud, like clay, and is often spoken of as a clay soil, but when dry it easily falls to powder.

The behavior of soils upon drying is a matter of great practical importance. Some soils in drying crumble easily, while others form clods which are difficult to break down. This behavior depends to a certain extent upon the amount of water present. Some soils crumble easily when plowed in the right condition, but when too much water is present they form intractable clods.

Cohesion may be determined in the dry state, or the wet state. For dry cohesion, the soil is mixed with water, molded into cakes of uniform size, and dried. The amount of force required to crush the cakes is then determined. This throws light on the liability to form clods.

For moist cohesion, the soil is mixed with water to 50 per cent. of its water capacity, and the power required to separate a section of the soil of a given area determined. This is related to the plowing of the soil.

The ease or difficulty of plowing or cultivating a given field depends largely on the cohesion of the soil. A measure of this is the draft of the plow. The draft of a plow on sandy soil may be as low as 27 pounds per inch in depth of furrow, as against 100 pounds per inch for clay. This means that the former would be light work for one horse, the latter heavy work for three horses.

Increasing the amount of organic matter in the soil has the effect of decreasing the cohesiveness of clays, and increasing it for sands. A dressing of lime also tends to decrease cohesiveness of a soil.

The state of dryness has an influence. Sand, lime, and humus have little adhesion when dry, but considerable when wet. Clay, under certain conditions of moisture, is very hard to plow. The English practice of burning clays overcomes adhesion. When clay is burned and then crushed, the particles no longer adhere tenaciously when wet, and the mass is sandy-like rather than clayey.

Shrinking on Drying.—Some soils increase in bulk when they become wet, and shrink on drying. The shrinkage is very perceptible in some clay soils. They become full of cracks and rifts on drying, and, since they harden about the rootlets imbedded in them, the roots may become ruptured during dry weather. Heavy clays may thus lose one-tenth or more of their volume.

Sand does not change in bulk on wetting or drying, and, when present to a considerable extent in the soil, its particles prevent the adhesion of the clay particles. Although a loam shrinks on drying, the lines of separation are more numerous and less wide than in a clay.

Some soils crack into comparatively small masses on drying. These are often termed *buckshot* soils. Others crack into larger masses, several feet in size. In others irregular cracks are found, sometimes an inch in width. Schubler prepared cubes of various soil constituents and determined the contraction in volume on drying. Pure clay contracted 18.3 per cent. of its volume; humus from the center of a decayed tree 20 per cent.; a sandy clay 6 per cent.; an arable soil 12 per cent.; a garden soil 14.9 per cent. The rifts allow an easier drying of the subsoil. The results of drying are afterwards favorable in a clay soil, the fissues affording drainage lines. The texture is improved, drying and moistening being favorable to formation of compound particles. Air is also admitted to the subsoil, and oxidation in the subsoil is promoted.

Number of Particles in Different Types of Soil.—These have been calculated by Whitney[1] as follows:

Early truck	1,955,000,000
Truck and small fruit	3,955,000,000
Tobacco	6,786,000,000
Wheat	10,228,000,000
Grass and wheat	14,735,000,000
Limestone	19,638,000,000

The basis of this calculation is the assumption of a certain average size for each grade of soil particle. Knowing the size and the specific gravity of the soil, the weight of each grade of particle can easily be calculated. Then the numbers of particles

[1] Bulletin 21, Maryland Station.

of each size can be calculated from the weights of the various separations made in the physical analysis of the soil.

Relation of Fineness to Fertility.—The state of division of a soil has some effect upon its fertility. If two portions of a rock are prepared, one coarse, and the other finely ground, plants will grow better on the latter. With the same material, the rapidity of solution is in direct ratio to the extent of surface it exposes. The finer the particles, the more abundantly will the plant be supplied with the necessary nourishment. For example, a cube of rock 1 foot square has 6 sides each 12 inches square, or 6 times 144 square inches of surface. Cut this cube into cubes of 1 inch square, or 12 times 144 cubes, each of which has six sides, one inch square, or the exposure is 6 times 144 square inches. It is easily seen that as the division increases, the surface exposed to the action of roots also increases.

It must not be assumed, however, that finely pulverized sandy soils would yield the same amount of plant food as clay soils. While this might be true in exceptional cases, as a rule sandy soils contain less plant food, as may be shown by a complete chemical analysis of the soil.

CHAPTER VII.

THE SOIL AND WATER.

The plant food is dissolved in water and enters the plant through its roots. Water also serves as the medium by which matter is transferred, and it supplies the hydrogen and a part of the oxygen used in the synthesis of organic matter.

A large amount of water is required by plants, not only because plants contain considerable water, but also because the passage of water through plants is one of the most important means of plant nutrition. The evaporation of water from the surface of the leaves produces an upward current of water which carries into the plant needed mineral material. The greater the evaporation, the greater is the transference of plant food from the soil to the plant, other things being equal.

Transpiration.—The loss of water through the leaf of the plant is termed *transpiration*. The amount of loss by transpiration is easily determined with plants in pots.[1] We weigh the pot of soil containing the plants at the beginning of the experiment and at the end of certain periods weigh it again; the loss of weight plus any water added, is water evaporated by plant and soil. The water evaporated from a pot of similar soil but with no plants, under the same conditions, is taken to show the evaporation from the soil alone, although the shade of the plant makes a difference. The loss of water by soil and plants, less the loss from soil alone, gives the loss by the plant alone. Correction must be made for the increase in weight of the plant, if the experiment is conducted for some time. In another form of apparatus, the soil is covered with a galvanized iron cover, and the openings through which the plant extends is rendered water-tight by means of modelling clay. Plants may be grown in the free air by this apparatus, without danger of irregular results due to varying amounts of rain falling in different pots of the same series.

If the plant is contained in pots or other vessels set in the

[1] Montgomery, Proc. Am. Soc. Agron., 1911, p. 257.

ground, or if it is too large to be weighed, the evaporation of water may be estimated by determining the quantity of water in the vessel at the beginning and at the end of the experiment (by analysis of the soil), and measuring the quantity of water received by the vessel during the course of the experiment.

In the transpiration experiments of the Bureau of Soils, the plants are grown in wire baskets covered with paraffin. Before the measurements of transpiration are begun, the pot is sealed with a sheet of paper coated with paraffin so as to exclude evaporation as much as possible, a suitable hole being left for the plants. The pots are weighed, and the loss of water is restored daily.

Factors of Transpiration.—The amount of water transpired by plants depends upon several factors:

Humidity of Air.—Transpiration decreases as the humidity of the air increases, for evaporation into dry air is much more rapid than into moist air. At the Nebraska Experiment Station,[1] plants were grown in an open greenhouse, in which the air was dry, and in a closed greenhouse in which floors and benches were kept wet, and water atomized into the air. The weights of water transpired per gram of dry weight, were as follows:

In dry greenhouse	340
In moist greenhouse	191

Available Water.—Plants appear to transpire more as the available water increases. The following figures show the amounts of water transpired from the same soil containing different quantities of water:

Per cent. saturation	Grams water used per grams dry weight produced
100	290
80	262
60	239
45	229
35	252

The plants grown with 35 per cent. saturation of the soil, did not grow normally.

[1] Montgomery, Proc. Am. Soc. Agron., 1911, p. 276.

Light.—More water is transpired in the light than in darkness. For example, Deherain[1] determined the water evaporated per hour and 100 grams of leaf, to be as follows:

WATER EVAPORATED.

	Wheat	Barley
	Grams	Grams
In sunshine	88.2	74.2
In diffused light	17.8	18.2
In darkness	1.1	2.3

On the other hand, excess of light may diminish transpiration.

Composition of the Soil or Solution.—The solution brought in contact with the roots or stem of a plant exerts a decided influence upon the amount of water transpired. According to Burgerstein,[2] small quantities of acid added to distilled water increase transpiration, alkalies retard it, and the effects of salts depend upon the nature and concentration of the solution. With single salts, transpiration increases with the concentration of the solution, until a maximum is reached. The effect of mixtures of two or more salts depends upon the nature of the salts used. Of greater agricultural importance is the fact that a complete nutritive solution decreases transpiration. The following table gives some examples:

The fertility and nature of the soil also appear to exert an

Salts	Period (hours)	Grams water transpired per 100 grams dry matter	
		With distilled water	With 0.170 per cent. solution of the salts named
		grams.	grams.
Potassium and calcium nitrates	94	1,838	1,142
Potassium nitrate and phosphate	96	1,670	1,161
Potassium nitrate and magnesium sulphate	120	2,794	1,939

[1] Jahresber. f. Agr. Chem., 1868, p. 273.

[2] Jahresber. f. Agr. Chem., 1875, p. 388.

influence upon the quantity of water transpired. Widstoe[1] found that the transpiration of corn is from 552 per gram dry matter on a loam, to 1616 on a sand or clay.

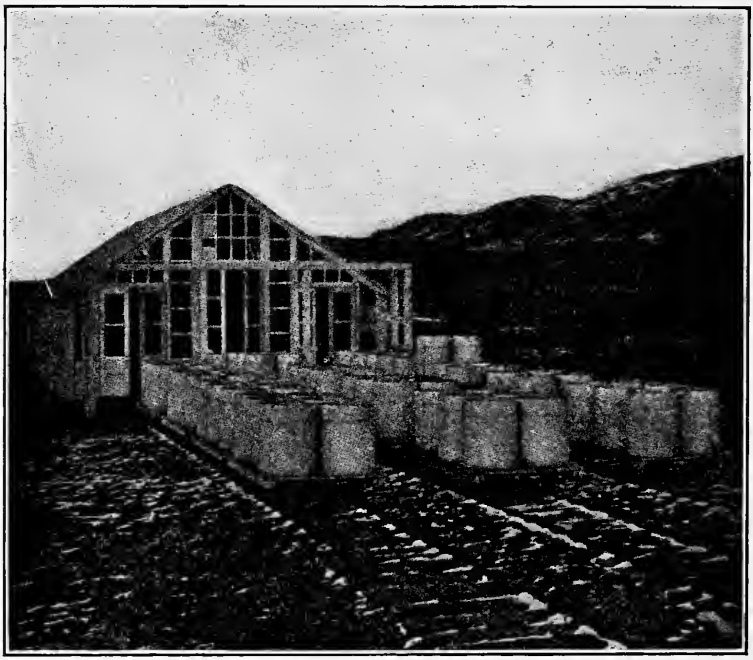


Fig. 32.—Pot experiments, on moisture used by plants. Utah Station.

Demoussy, at the Grignon Experiment Station, found that the poorer the soil, the more water was transpired. The following figures are quoted from him.

GRAMS OF WATER TRANSPIRED PER 1 GRAM DRY MATTER PRODUCED.

	Rye grass	Clover[2]
Exhausted soil	630	454
Exhausted soil with chemical manure	233	398
Exhausted soil with liquid manure	435	255
Exhausted soil with liquid manure	449	272
Manured regularly	630	322

[1] Utah Bulletin, No. 105.

[2] Not manured the same as the rye grass.

In some pot experiments of König, similar results were secured. The relative quantity of crop he produced on three soils was 100: 122: 134, while the relative transpiration of water was 100: 74: 63, being in the opposite direction. Gardner[1] found in wire basket experiments, that as fertilizers increase plant growth, there is a marked diminution in water transpired per unit of growth.

It would appear that a fertile soil conserves moisture, so far as transpiration is concerned, much better than a poor one. That is to say, the better supplied a soil is with plant food, the larger is the crop which it can produce with a limited supply of water. The presence of plant food results in an economy of water. The smaller the quantity of available plant food present, the greater seems to be the effort made by the plant to secure sufficient plant food, by increasing the current of water passing through it.

Results of an experiment with corn on soil types at the Nebraska[2] Experiment Station, are as follows:

Character of soil	Water transpired per gram	
	Unmanured	Manured
Very poor (15 bu.)	540	350
Intermediate (30 bu.)	478	341
Quite fertile (50 bu.)	391	346

Variety of Plant.—The difference in the transpiration of different kinds of plants is probably a factor in the adaptability of plants to climate and soils. Plants which live in dry regions, such as cactus, salt bush, etc., transpire less water than plants adapted to moist sections. There are other causes of endurance of drought, however, such as the deeper rooting already discussed.

According to Fittbogen there is no relation between transpiration and the production of organic substance, as measured by the carbon dioxide decomposed.

[1] Bureau of Soils, Bull. 48.

[2] Proc. Am. Soc. Agri., 1911, p. 277.

Amount of Water Required by Plants.—The amount of water transpired during the growth of a plant may be calculated as parts of water per one part of dry matter of the plant, and may be considered to represent the amount of water required by the plant. This quantity will vary considerably according to the conditions surrounding the plant, as we have seen in the preceding paragraphs. An estimate of the amount of water required to produce a given weight of dry matter is, therefore, only approximate. Such an estimate may, however, aid in the consideration of problems relating to the water content of the soil. The figures given in the table were secured in experiments of four investigators.[1]

Pounds of Water Evaporated by the Plant per Pound of Dry Matter Produced.

	Lawes and Gilbert	Hellriegel	King	Wollny
Barley	262	310	393	774
Beans	214	262	—	—
Buckwheat	—	371	—	646
Corn (maize)	—	—	272	233
Clover (red)	249	330	453	—
Lupine	—	373	—	—
Millet	—	—	—	416
Mustard	—	—	—	843
Oats	—	402	557	665
Peas	235	292	477	447
Potatoes	—	—	425	—
Rape	—	—	—	912
Rye	—	377	—	—
Sunflower	—	—	—	490
Wheat	225	359	—	—

In some of the arid states of the United States, fair crops of wheat are grown with an annual rainfall of 13 to 18 inches, most of which falls in the winter before the growing period of the crop begins. This small quantity of water is effective, partly because the soils are rich in soluble plant food, partly because the saline matter in solution decreases transpiration.

[1] Exp. Sta. Record 4, 532, Rep. Wis. Station, 1894; Jour. Hort. Soc. Eng., 1850. See also Widstoe, Utah Bul. No. 105; Montgomery, Proc. Am. Soc. Agri., 1911, p. 261.

In regions of deficient rainfall, the crop produced is, as a rule, somewhat proportional to the water supply. S. Fortier[1] in Montana made experiments with wheat grown in tanks. The crop secured increased quite regularly with the amount of water

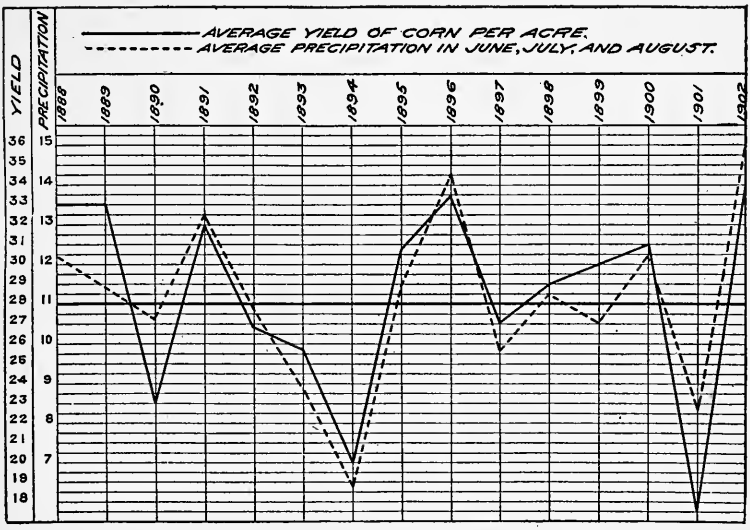


Fig. 33.—Relation of rainfall for June, July and August to yield of corn per acre. U. S. D. A.

supplied. In California, he found that the natural rainfall, 4½ inches during the growth of the wheat, produced straw, but no grain; four inches of irrigation water produced at the rate of 10 bushels, and sixteen inches of water increased the yield to thirty-eight bushels per acre. Even in humid climates, irrigation may result in largely increased yields.[2] King[3] in Wisconsin grew crops in barrels sunk level with the ground surrounded by the same crop as was in the barrel. The soil was kept saturated with water six inches above the bottom of the barrel. The crops produced far exceeded those produced in the surrounding field. The water used equaled 24 inches. The yield of oats and barley

[1] Rep. Montana Exp. Sta., 192-3.
[2] King, Farmers' Bulletin No. 46.
[3] Rep. Wis. Exp. Sta., 1893.

was 10,000 pounds dry matter per acre. The abundant supply of water thus had a striking effect.

Smith[1] has studied the relation of the rainfall to the yield of corn. Figure 33 shows the relation between the average yield of corn in bushels per acre, and the rainfall, in Ohio, Illinois, Indiana, Iowa, Nebraska, Kansas, Missouri, and Kentucky for the years 1883 to 1902 inclusive.

Duty of Water.—Duty of water is a term applied by irrigators as the measure of the quantity of water used per acre, but the term is also applied to the service which water may render in producing crops. McGee[2] estimates that it requires approximately 1,000 pounds of water during the year to produce one pound of grains, etc. This estimate allows for losses by evaporation, and its basis is the aggregate yearly supply of water from all sources. He presents the following table, based on personal observation, showing estimates of crop yields with varying amounts of water for the entire year:

Depth per acre	Corn	Oats	Wheat
	bushels	bushels	bushels
18 inches	10	15	6
36 inches	35	40	12
48 inches	70	80	25
60 inches	105	120	40

These figures, are roughly approximate, as there are great variations in conditions. According to this table, 36 inches yearly rainfall will produce, on an average, 35 bushels of corn.

Quantity of Water in Soil.—The following figures of Hellriegel[3] are the result of an experiment to ascertain the effect of the amount of water in the soil upon the crop production. The experiment was carried out in pots.

[1] Yearbook, U. S. Dept. Agr., 1903, p. 216.
[2] Yearbook, U. S. Dept. Agr., 1910, p. 174.
[3] Jahresber, f. Agr. Chem., 1870-2, p. 161.

Effect of Moisture on Crop.

Moisture in percentage water capacity of the sand	Barley	
	Total	Grain
80	19.69	8.77
60	22.76	9.96
40	21.76	10.51
30	17.19	8.70
20	14.62	7.75
10	6.30	0.72
5	0.12	—

The most favorable quantity of water in this case was 40 per cent. of the water capacity of the sand. Necessarily in this respect there will be a difference for different kinds of plants.

According to this experiment, there is an optimum condition of the soil at which the moisture content is most favorable to plant growth. Below or above this optimum, there is a decrease in yield, independent of the wilting of the plant. Wilting is a sign of distress, signifying that moisture is lacking to an extent that endangers the life of the plant. The growth may suffer from lack of water long before wilting takes place. The experiments of Hellriegel were carried on in pots, in which there was a limited amount of soil at the disposal of the plants. In the open field, in which a greater range of root development is permitted, a smaller percentage of available water may suffice.

Forms of Water in the Soil.—Water is present in the soil as water of hydration, hygroscopic water, capillary water, and flowing water.

Water of hydration is water in chemical combination with certain soil constituents, such as hydrated silicates (zeolites) and hydrated oxide of iron. Most of it is retained when the soil is dried at 100°, and is driven off on heating the soil to a high temperature. As water of hydration cannot be taken up by plants, it cannot be considered to be of value to the plant.

Hygroscopic Water is water which is absorbed by the soil from the atmosphere. Every body in a moist atmosphere has a layer of water upon it, the thickness of which depends upon the tempera-

ture and the degree of saturation of the atmosphere. The capacity of the soil to hold hygroscopic water can be determined by placing a thin layer of soil in a vessel, the air of which is saturated with water; the soil will take up a certain amount of water, which can be determined by the gain in weight of the soil. The temperature of the containing vessel must be uniform, for variations in temperature in a saturated atmosphere will be liable to form dew on the soil. The layer of soil must be very thin, not over one millimeter thick. This method gives the maximum hygroscopic capacity; if the air is not fully saturated, lower results will be obtained.

The amount of hygroscopic water taken up depends very largely on the character of the soil. According to Hilgard and Loughridge,[1] soils absorb the following amounts of hygroscopic moisture:

	Hygroscopic moisture Per cent.
Sandy soils (less than 5 per cent. clay)	3
Sandy loams	3–5
Loams	5
Clay loams	5–7
Clay	7–10

The amount of hygroscopic water taken up by a given substance depends partly upon its surface area. A mass of quartz will absorb much more moisture when in fine powder than when in large fragments. It is also greatly influenced by the amount and character of the colloid constituents in the soil, such as hydrated ferric oxide, alumina, gelatinous silica, hydrated silicates, and especially humus. Pure clay has a somewhat lower absorptive power than these.

Value of Hygroscopic Moisture.—Plants are not able to utilize the hygroscopic moisture of soils. At least, they wilt before the moisture in the soil is withdrawn to the amount held by hygroscopic power.

Heinrich[2] grew plants in very small boxes until well developed

[1] Rep. Cal. Exp. Sta., 1897-8.

[2] Jahresber, f. Agr. Chem., 1875-6, p. 368.

and then placed them under conditions of very little evaporation until they began to wilt. The moisture in the soil was then determined. The hygroscopic moisture was also determined by the method already indicated. A variety of soils and plants were used. The following table shows the average results secured with Indian corn and oats:

	Water per 100 of dry soil	
	When plants wilted	Hygroscopic water
Coarse sandy soil	1.5	1.2
Sandy garden soil	4.6	3.0
Fine humus sand	6.2	4.0
Sandy loam	7.8	5.7
Calcareous soil	9.8	5.2
Peat	49.7	42.3

It appears that hygroscopic water may be of advantage in regions of hot, dry winds; the higher the hygroscopic water, the less rapidly the soil dries out and heats up. It also appears that heavy fogs, such as occur in parts of California, may add to the hygroscopic water of the soil, and keep the plant growing slowly when rainfall is lacking.

Capillary Moisture.—This is the thin film of water surrounding the soil particles and so held between them that it cannot flow off. In a clean glass tube of 1 mm. internal diameter, capillary attraction will cause water to rise 15.3 cm; if the bore is 0.1 mm. the water will rise 153.6 cm; if it is 0.01 mm. the water will rise 1536.6 cm. That is, the height to which the water is carried varies inversely as the diameter of the tube. It also varies with the temperature and the liquid used.

If glass tubes be filled with various soils and the lower ends of these be set in water, a great difference will be observed, both in the speed and in the height to which the water rises in them. This is the method used for comparing the capillarity of dried soils.

The following table[1] exhibits the differences in the height to which water rises in some soils:

[1] Meister, Jahresber. f. Agr. Chem., 1859-60, p. 42.

	5½ hours	21½ hours
	inches	inches
Clay soil	44	80
Humus soil	44	70
Garden earth	38	64
Quartz sand	37	45
Sandy soil	26	36
Chalky soil	21	28

Briggs and Lapham[1] found that water rose 37.5 cm. in a dry soil, while in a moist soil it rose over 165 cm. The method of work was as follows:

Two tubes of glass were provided with perforated bases, filled with soil, and saturated with water by sucking it up through the earth. One tube was then sealed at the base, and the other inserted into a reservoir of water. At various intervals of time, both tubes were weighed. If water rises by capillary action, the tube with reservoir attached will lose water more rapidly than the other one. If not, a section of the tube was removed after a suitable interval, and the operation repeated. For example, with one soil, no loss occurred at 180 cm.; loss occurred at 165 cm. The capillary water rose 165 cm., but did not rise 180 cm.

The so-called capillary moisture of the soil is held as thin films of water surrounding the soil particles, due to what is called "surface tension." The surface of the film of water surrounding the soil particle is in the condition of an elastic membrane exerting considerable pressure and consequently holding the water firmly against the soil particle. In a fully drained soil there is a condition of equilibrium between the force of surface tension and the force of gravity. If the film of water becomes thicker and heavier, the force of gravity will gradually draw away the excess of water. If the films become thinner, a force is developed which may cause a flow of water from thicker neighboring films.

Loughridge[2] studied the capillary action of soils placed in copper tubes one inch in diameter and in one foot lengths, fitting

[1] Bulletin 19, Bureau of Soils.

[2] Rep. Cal. Exp. Sta., 1892-4

into each other. One side of the tube was made of glass so that the contents might be observed. The bottom tube was closed at its lower end with muslin and the tubes filled with air-dry soil, stirred in with a wire and made firm by a slight tapping on the table. In experiments with a sandy soil, an alluvial soil, a silty soil, and an adobe soil, water rose rapidly in the two coarser soils, reaching 8 to 9 inches in the first hour, while the water in the stiff soil rose only 1 to 2 inches. The water rose rapidly in the sand, but only reached a final height of 16½ inches. The other three soils, in 125 or 195 days, reached nearly the same height, but the alluvial soil, composed mostly of fine sand and silt, carried the water up most rapidly. This experiment is an instructive illustration of the difference in the capillary powers of soils.

Water thus tends to distribute itself in the soil, through capillary passages or by the slower processes of surface distribution. When these operations are assisted by gravitation, as when rain falls, the water moves rapidly. When the movement of water is opposed by gravitation, as when a soil dries at the surface and is wet below, the movement is retarded by the increasing height of the column of water lifted, until finally it entirely ceases.

Capillary action has some effect in raising water from the water table in a few instances when the water table is less than about four feet from the surface. One great function of capillary action and surface tension is to distribute water to the roots. When water is withdrawn at one place by the roots, it disturbs the equilibrium and causes a flow of water from points of least resistance.

Flowing Moisture.—Water present in excess of the hygroscopic moisture held by capillary action, may be termed flowing water. It will pass downward through the soil at a rate depending upon the permeability of the soil.

The quantity of water in a saturated soil depends entirely upon the air space in the soil. The soil is saturated when all the air space is filled with water. The air space can be calculated from the real and the apparent specific gravity of the soil.

Sand and gravel separately have an air space corresponding to about 40 per cent. of their total volume. When mixed together, the small particles of sand enter the free space of the gravel, and diminish the volume of the free space. In ordinary soils, the volume of the free space is somewhat greater than in sand or gravel, owing to the presence of porous or compound particles. A soil abounding in porous compound particles decreases in water capacity when reduced to a powder. Zenger found that the soil from a peaty meadow held 178 parts water to 100 parts soil, but it held only 103 parts water when finely powdered. Colloidal bodies take up water and make the soil swell when wet.

A soil is seldom completely saturated under natural conditions. The soil cannot become fully saturated unless the air which fills the interstices of the soil is allowed to escape. Rain covers the surface of the soil and closes the path of the air so that it gets out with difficulty. Only after long continued rains do soils become nearly saturated.

The following table shows the quantity of water in naturally saturated soils, the samples being collected after continued rains:

	Water in naturally saturated soils	
	Parts per 100 of wet soil	Parts per 100 of dry soil
Quartz sand	18.4	22.5
Clay loam	22.4	28.9
Brick clay	24.1	31.8
Black marsh	25.7	34.7
Loam, no manure 26 years	23.0	29.9
Loam, artificial manure 26 years	24.7	32.8
Loam, barnyard manure 26 years	37.6	60.2

The first four analyses were made by King.[1] The last three samples, from the Rothamsted[2] Experimental fields, show the effect of humus upon the water capacity. The accumulation of humus in the soil manured with barnyard manure increases the water capacity of the soil decidedly. On account

[1] Wisconsin Report, 1890.

[2] Jour. Roy. Agr. Soc., 1871, p. 110.

of the larger amount of stubble left by the crop produced with a complete mineral fertilizer, this soil also holds more water than the one with no manure.

Method of Expressing Water in Soils.—The amount of water contained in a soil may be expressed in three ways[1]; first, in terms of the volume of water which occupies a given volume of soil; second, in percentage of water contained in the wet soil; third, in percentage of the dry soil. The following table (after Warington) gives the water in some soils fully saturated:

	Water in saturated soils		
	Volume of water per 100 volume of soil	Water by weight	
		In 100 of wet soil	Per 100 of dry soil
Coarse sand	39.4	19.8	24.7
Sandy soil	45.4	23.3	30.4
Chalk soil	49.5	28.2	39.2
Clay	50.0	27.8	38.5
Loam	60.1	31.2	45.4
Garden earth	69.0	43.4	76.8
Peat subsoil	84.0	78.2	259.0

It is better to compare volumes of water in given volumes of soil in considering the water content of different soils. The roots of the plant are distributed through a given space, which varies according to the kind of plant, depth of soil, etc., and it is the quantity of water and plant food in the space occupied by the roots which is important. This method of expression is, however, cumbersome; for, in addition to the weight of soil and weight of water, there must enter into the calculation the real and apparent specific gravity of the soil.

The expression of the water absorbed in terms of the weight of the dry soil has decided advantages, especially in laboratory work. Only two quantities are involved, the weight of the soil and the weight of the water. It is thus easy to calculate the amount of water which should be present in a given weight of soil to produce a definite degree of saturation.

[1] Warington, Physical Properties of Soils, p. 69.

Expressing the water present by weight in 100 parts of dry soil exaggerates the differences between soils. This is most marked when peat is compared with a sand, for we really compare the water in seven volumes of wet peat with one volume of wet sand.

Retention of Water by the Soil.—A soil, though protected from evaporation, does not remain fully saturated, but loses water through capillary action and the action of gravity. If a wide tube of sufficient length, filled with coarse sand of uniform sized particles, is saturated with water and allowed to drain, we find two distinct layers; a short column of sand fully saturated, and a long column above it fully drained, and containing a nearly uniform quantity of water.

If the particles of sand are not uniform in size, as in an ordinary soil, then we find three layers, but not sharply distinct as in the preceding case. The highest layer is fully drained, and the content of water of the soil increases, until the lowest layer is fully saturated. The water in the fully drained layer not only coats the particles but fills the finest of the interspaces. The proportion of interspaces occupied by water increases toward the bottom of the tube, until finally all the interspaces are filled and the soil is saturated.

The following experiment of King[1] exhibits the differences between two classes of soil material. Tubes 10 feet long and 6 inches in diameter were filled with sand prepared by sifting through sieves of different degrees of fineness. The sand was saturated with water, and allowed to drain, protected perfectly from evaporation, for 111 days. The water in each 6 inches of the columns was then determined. Two of the series are shown in the table.

The particles in tube I are nearly uniform; the water content is nearly constant until the ninth foot is reached, when it suddenly increases. The particles in tube II are of varying size; the water content increases constantly from the top to the bottom.

The amount of water retained by a drained soil depends upon the smallness of the spaces between the particles, and also on

[1] Report Wisconsin Station, 1893.

whether or not the particles are porous. The smaller the particles and the more porous they are, the greater the quantity of water held. Humus and other organic matter, being porous, increase the water retained considerably.

	I Particles 1/60″ to 1/80″	II Particles less than 1/100″
	Per cent.	Per cent.
First foot	2.40	3.35
Second foot	2.72	3.53
Third foot	2.79	4.03
Fourth foot	2.93	5.16
Fifth foot	2.98	6.99
Sixth foot	3.12	9.83
Seventh foot	3.11	10.98
Eighth foot	3.54	15.88
Ninth foot	13.50	18.90
Tenth foot	20.51	19.59

The water held by drained soils may be determined by placing the soil in tubes which can be divided into sections, as in the experiment of King cited, though the tubes need not be so large. After the soil has been saturated and is fully drained, the water is determined in the different sections. Unless the tube is sufficiently long, the upper sections will not be fully drained. The length of tube required depends upon the character of the soil. The following figures of Schloesing show the quantity of water held by fully drained soils:

	Weight of water in 100 parts of drained soil
Coarse sand	3.00
Fine sand	7.30
Calcareous sand	32.00
Clay soil	35.00
Forest soil	42.00

The state of consolidation of soil affects the water held by it. Closely packed particles will retain at least twice as much water per unit of volume as particles loosely packed. Sandy soil has its capacity increased by rolling, and that of clay soil is reduced by pulverization.

Water Capacity.—The water capacity of a soil is the amount of water held by the partly drained soil. Fifty grams of soil are placed in a tube 1¼ inches in diameter, allowed to drain, and weighed. The gain in weight, expressed in per cent., is the water capacity. Other methods which vary in detail are used. The percentage of water held will vary with the height of the column of soil, and to some extent, with the time of draining, but the results are comparable if the same method is used on different soils.

The following figures show the water capacity of some types of soils, determined by the method given above:

	Water capacity of some soils[1] Per cent.
Tarboro sand	25.1
Norfolk sand	29.6
Cecil clay	45.0
Cecil sandy loam	36.8
Durham sandy loam	28.9

Amount of Water at Disposal of Plant.—The amount of water at the disposal of the plant varies from time to time, according to a number of factors. The principal groups of factors are as follows: (1) The available water in the soil; (2) the root area of the plant; (3) the losses and gains of water by the soil; (4) the depth of the water-table.

Available Water in the Soil.—The amount of available water in the soil depends upon the nature of the soil, and the nature of the plant.

Nature of Soil.—The forces which cause water to enter a plant are opposed by the osmotic pressure of the soil solutions and by the hygroscopic attraction of the soil particles for water. The soil attraction increases as its moisture content diminishes, consequently decreasing the rate of entrance into the plant, and diminishing the production of organic substance if the amount supplied is below the optimum. When the outgo of water becomes greater than the income, the plant wilts. The point at which wilting takes place varies with the nature of the plant, but

[1] Rep. N. C. Exp. Sta., 1902-3, p. 39.

depends also on the nature of the soil, the temperature, and the humidity of the air.

Briggs[1] and associates have elaborated methods for the determination of the wilting point of plants, and traced the relation between the moisture content of the soils at the time of wilting, and the moisture equivalents of the soils, their hygroscopic power and their capacity to hold moisture. The moisture equivalent is the percentage of moisture the soil will retain in opposition to a centrifugal force 1,000 times the force of gravity. The relations between these factors he expresses as follows:

$$\text{Wilting coefficient} = \frac{\text{moisture equivalent}}{1.84} = \frac{\text{hygroscopic co-efficient}}{0.68} = \frac{\text{moisture-holding capacity} - 21}{2.90}$$

The water which cannot be withdrawn from soils by a plant may be termed unavailable water, and that in excess of this, available water. The California Experiment Station holds the available water to be practically the hygroscopic water, that is, the moisture absorbed from the soil by a damp atmosphere.

Nature of the Plant.—Plants vary in their power of absorbing water from soils. That is to say, some plants will reduce the water in the same soil to a lower percentage than others, before wilting. This may be due in part to difference in the ratios between root area and surface growth, enabling a lower rate of water to supply the requirements of the plant; or to greater root attraction for water by some plants, causing a larger flow of water into the one plant than in the other, under the same conditions of soil moisture; or to differences in the amount of water transpired.

During a severe drouth, the California Experiment Station[2] determined the amount of water in a large number of soils, where plants were doing well, or were suffering. California soils, it must be recalled, are different from soils of humid climates, there

[1] Proc. Am. Soc. Agr., 1910, p. 138; 1911, p. 250; Bul. 230, Bureau of Plant Industry.

[2] Report 1897, p. 95.

being no distinction between subsoil and surface soil, the roots thus being able to strike deep into the soil. For this reason smaller quantities of water may suffice for crops. The results are as follows:

Available water per cent.	Doing well	Suffering
1	Apricots	Citrus
1-1.5	Citrus	Almonds
1.5-2	Almonds	Barley
3-4	Pears	Wheat
4-5	Wheat	
5-6	Sugar Beets	

Root Area of Plants.—The greater the volume of soil occupied by the roots, the greater the quantity of water (and also of plant food) at the disposal of the plant. Hence operations which deepen the surface soil or loosen the subsoil, so as to allow the roots to penetrate more deeply, have a favorable effect upon the amount of water offered to the plant. The volume of soil occupied by plants depends upon the nature of the plant.

Water-Table.—The water-table is the depth at which the soil is saturated with water, and is indicated by the depth of the water surface in shallow wells, which is slightly below the water-table. The water in the water-table is termed *ground water*. All permanent lakes and ponds may be considered as extension of the water-table above the surface of the land. The surface of the water-table follows, in a general way, the contour of the land, standing highest where the ground is highest, and low where the land is low. Land at the foot of hilly ground may receive a continuous supply of underground water, even in time of drought.

If a bed of impervious clay is present in the subsoil, the underground water accumulates on its surface. The water level may generally be lowered by drainage ditches or tile drains.

The height of the water-table depends upon the character of the soil, the rainfall, and the climate. It usually fluctuates, rising during wet seasons and sinking during a drought. When the height of the saturated layer reaches a certain point, discharge takes place in the form of springs or as general drainage.

If the water-table is only a few inches beneath the surface, we have a swamp or bog; at one and a half to three feet in depth, we have a wet soil in which some plants, especially grasses, may flourish. A depth of four to eight feet is favorable to agricultural conditions, though in many regions the water-table is much lower than this.

In general, agricultural plants are injured if their roots are immersed for any length of time in the ground water, though many plants may send down roots to this water.

Gains of Water by the Soil.—The chief ways in which the soil may gain water are by rainfall and irrigation. In addition, ground water may be brought up to within reach of the plant roots by capillary action.

Regions having more than 20 inches rainfall are said to have a humid climate. The character of the rainfall must be considered as well as the total quantity. If it is heavy and infrequent, a large proportion of the water will run off on the surface and the region may possess more characteristics of an arid climate than a region with a moderate rainfall well distributed.

The amount of water gained from rain depends upon the nature and the extent of the rainfall, the drainage, etc. A heavy, rapid rainfall may saturate the surface and flow off without any large quantity sinking into the soil. A slight rain may decrease the water content of the soil by establishing such capillary connection between surface soil and lower layers, as to bring water to the surface which is lost by evaporation.

If the surface of the soil is compact, the rain may flow off instead of penetrating the soil; but if the soil is loose, it will absorb considerable quantities of rain. One method of preventing the washing of hilly land consists in deep plowing or subsoil plowing, so that the water will sink into the soil instead of running off. In regions of slight rainfall, where it is desirable to save all the rain, the subsoil is stirred, and packed; this increases the capillarity of the soil and its power of holding water. These are the methods of dry farming.[1]

[1] See Dry Farming, by Widstoe.

Capillary Action.—If the water-table of the soil is so low that capillary action cannot raise water to the plant roots, it has no effect upon the plant. If it is within such distance that water can be raised to the soil's surface, the water raised by capillarity will tend to replace the water lost by evaporation and transpiration. The extent to which this replacement takes place depends upon the relative rates of evaporation and transpiration, and the rate of capillary action.

King[1] studied the amount of water which can be brought upward by capillary action, using cylinders 4 feet high and one foot in diameter, which could be supplied with water from below. The cylinder was partly filled with water, soil dropped in and stirred, and the operation repeated until the cylinder was filled. The water level was then lowered to one foot below the surface, and maintained at this point, while the surface of the cylinder was exposed for eight days to a strong current of air, and the quantity of water evaporated determined. The evaporation was determined for depths of 1, 2, 3, and 4 feet of the water-table. At the depth of 4 feet, the average evaporation from a fine sand and a clay loam was 0.9 pounds per day and square foot. In order for this experiment to be complete, it would be necessary to prove that this quantity of water passed upward from the water-table. The evaporation of the water may have been due, in part, to the natural drying of the soil, although it decreased as the water-table was lowered. In Wisconsin, crops in this soil suffer considerably from drought, though the water-table is only five feet from the surface, showing that in the natural condition the soil is able to raise but little water even a distance of five feet.

The effect of capillary action in bringing up water is also shown by the Rothamsted drain gauges. The shallow one is 20 inches deep, the deeper one 40 inches. On an average of twenty-five years, the annual evaporation from the deeper gauge is only 0.6 inches greater than from the shallow; this probably represents the quantity of water brought to the surface from below the depth of 20 inches.

[1] Report Wisconsin Station 1889-1890.

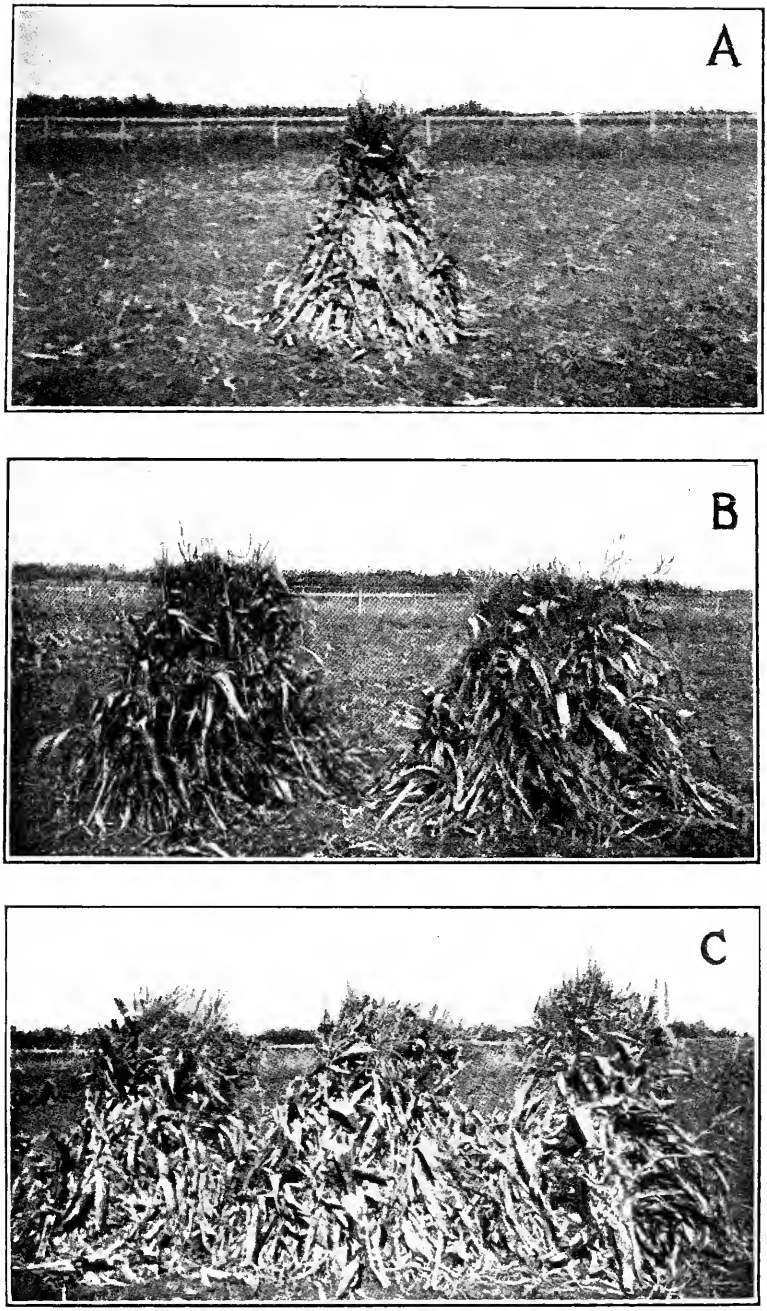


Fig. 34.—Corn on heavy clay soil (*a*) undrained (*b*) tiles 70 feet apart (*c*) tiles 44 feet apart. Wisconsin Station.

The roots of plants, however, may sometimes extend to considerable depths, and the presence of the water-table at a moderate distance from the surface, is thus an advantage.

If moist air comes in contact with a cold surface it will deposit water. A soil may gain water from the air when the air is moist enough and the surface of the soil cool enough. It has been thought that water is sometimes distilled, as it were, from the lower layers of the soil into the upper.

The monthly drainage from Mr. Greaves drain gauge[1] in England, filled with gravel and free of vegetation, has in fourteen years exceeded the monthly rainfall nineteen times; twice in December, seven times in January, seven times in February, and three times in March. The amount of water condensed from the air must, therefore, have been in each case more than that lost by evaporation from the soil, and may therefore increase the moisture of the soil. In Texas very heavy dews have been observed at various times. Drain gauges in England sometimes run more water than falls as rain, especially in January, February, and March.

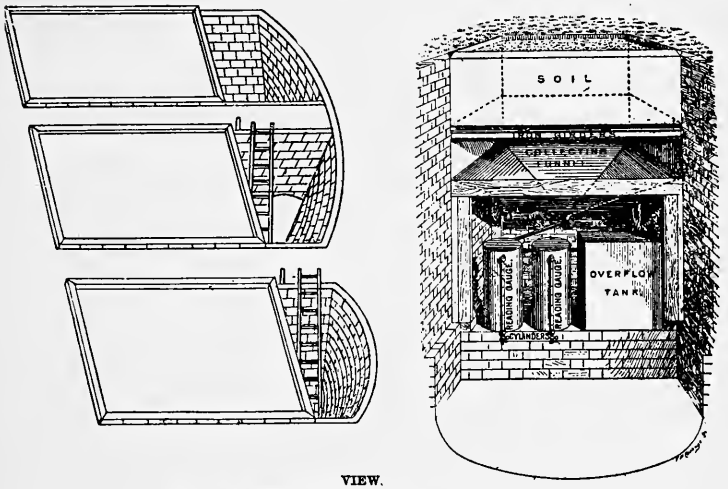
Losses of Water from the Soil.—The water which comes to the soil is lost in several ways. Part flows away without penetrating the soil, as *surface water*. Part percolates through the soil to the water-table and reappears in drains, wells or springs, or passes through subterranean channels to the sea; this may be called *percolation water*. Another portion of the water is evaporated from the soil into the atmosphere. Finally, the water taken up by plants is passed off through their leaves into the air (transpiration).

The proportion of the rainfall which passes off as surface water depends upon (*a*) the character and condition of the soil; (*b*) the slope of the land; (*c*) the amount and duration of the rainfall. If the soil is loose and porous, either naturally, or rendered so by cultivation, a larger amount of water will penetrate it. The slope of the land determines the rate at which the water runs off; the shorter the time of contact between soil and water, other

[1] Warington, Physical Properties of the Soil.

things being equal, the smaller will be the amount of water absorbed by the soil. The greater the quantity of water precipitated in a given period of time, the larger the proportion of it will run off as surface water. The more rapidly the water runs off, the more soil it carries along with it, and the more likely it is to do damage by washing.

Percolation.—The rate at which water passes through the soil depends upon the character of the soil and the treatment to which it has been subjected. Sands allow water to percolate rapidly,



VIEW.

3 Drain Gauges—
Each 7 feet 3·12 in. × 6 feet = $\frac{1}{1000}$th acre area:
Respectively 20, 40, and 60 inches depth of soil.
collectors, each holding Drainage = 0·500 in.
Gauge-tubes graduated to .. .. 0·002 in.
Overflow tank to hold Drainage. = 2·000 ins.

Fig. 35.—Drain gauges, Rothamsted, England.

and since they usually have a low capillary power, they often suffer from drought. Some clays allow water to pass through so slowly that they remain wet and heavy, do not warm up quickly, and are often hard to work. The amount of water which percolates may be decreased by increasing the water capacity of the soil or subsoil.

Drain Gauges.—Drain gauges are used to study the gains and

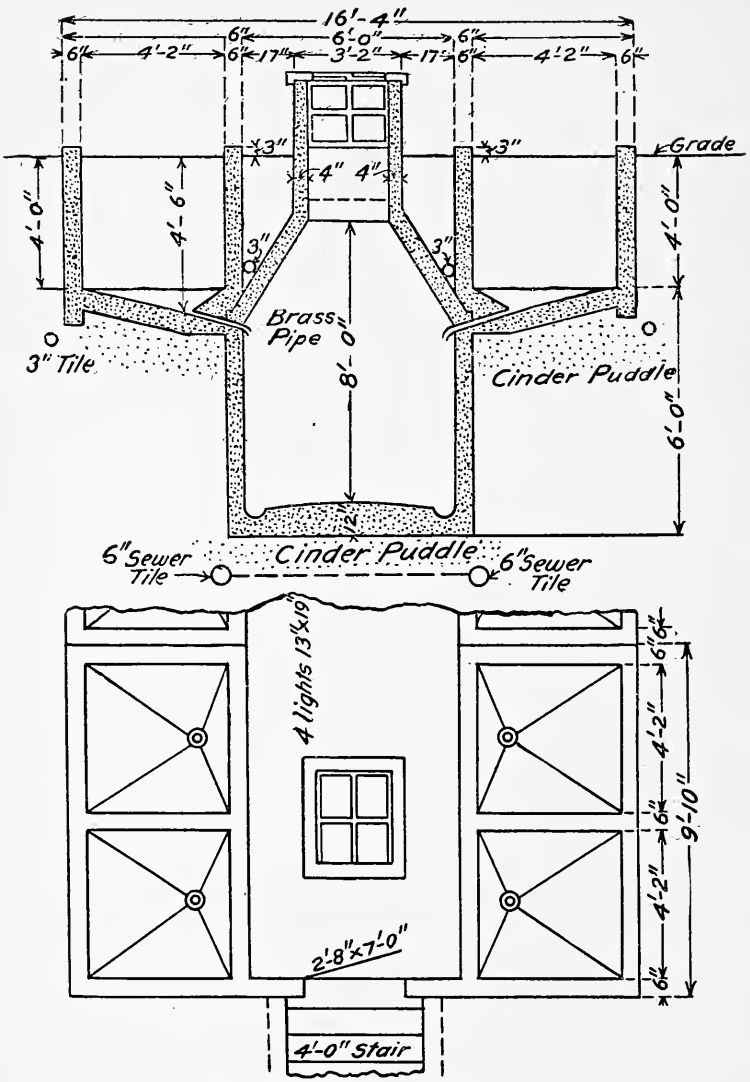


Fig. 36.—Concrete tubs for soil investigations, New York (Cornell) Station.

losses of water by percolation and evaporation. The composition of the drainage water may also be studied.

A drain gauge is a water-tight vessel filled with soil and exposed to the rain under natural conditions. The water which passes through a given depth of soil is collected, measured, and otherwise examined, as desired. The soil may be kept bare, or cultivated or planted to various crops. The drain gauges at Rothamsted are filled with undisturbed soil of that place. Excavations were made along the side of the block of earth desired; it was bricked up and isolated. Each drain gauge consists of a rectangular mass of heavy loams with flints, of an area of 1/1000 acre, 20, 40, and 60 inches deep, respectively. All the rainfall either passes through this mass of earth or evaporates. Drain gauges filled with loose earth represent unnatural conditions, and time should be allowed for the earth to consolidate before measurements are begun.

Another method of studying drainage waters is to measure the water going off through tile drains, but this is not a good method, since only the excess of ground water passes off through the drain. A large portion of the percolating water passes into the country drainage.

Evaporation.—The rate at which water is lost by evaporation depends upon the nature and moistness of the soil, its capillary condition, the temperature, velocity of wind, humidity of air, etc.

The wetter the soil, the less the humidity of the air, the greater the velocity of the wind, and the higher the temperature, the greater is the loss by evaporation.

If the upper layer of the soil is loose and porous, it will dry out quickly, and the rate of loss will then be influenced by the rate at which water is brought to the surface by capillary action. Evaporation is greatly checked if the connection between the top soil and the under layer is broken by cultivation. Evaporation is also influenced by the rapidity with which the water penetrates the soil. Much larger quantities of water will be lost by evaporation if the water is retained near the surface, than if it sinks into the soil.

The annual evaporation from the bare soil in the Rothamsted rain-gauges is apparently unaffected by the amount of rainfall. During nine years the rainfall varied from 22.9 to 42.7 inches; the evaporation from the shallow gauge varied from 16.6 to 18.4 inches, while the percolation varied from 5.6 to 25.5 inches.

The losses of water from soil carrying vegetation is greater than from a bare soil. In the rotation of crops, it is necessary to consider this fact. For example, King[1] determined the percentage of water in two portions of a field about to be planted to corn; one portion had previously been a bare fallow, the other had carried clover. The clover land contained much less water than the bare fallow land, and the corn on the bare fallow would thus be far better able to stand a summer drought. One injurious effect of weeds is to remove water from the soil.

Relation of Water Content to Evaporation.—In the following table (by Schubler) the amount of water absorbed by soils is compared with the amount of evaporation during four hours:

	Percentage of water held by soil	Percentage of water present evaporated
Quartz sand	25	88.4
Gypsum	27	71.7
Lime sand	29	75.9
Loam	51	45.7
Heavy clay	61	34.9
Pure gray clay	70	31.9
Fine carbonate of lime	85	28.0
Garden mold	89	24.3
Humus	181	25.5
Fine carbonate of magnesia	256	10.8

It is evident that the finer soils have not only a greater water capacity, but also allow less evaporation to take place.

Control of Water.—The control of water, so that plants may at all times receive the optimum amount, or as near it as possible, is one of the most important parts of agricultural practice and the chief object of many operations of tillage.

Control of the water supply is exercised by storing water in the

[1] The Soil, 191.

soil, by irrigation, by improving capillary conditions, by prevention of loss, by decreasing transpiration, by drainage. In regions where rainfall is deficient, especially during the crop season, it may be necessary to store up the rain as much as possible. Surface water may be conserved by plowing the soil before the rainy season. Due regard should be paid to proper ditching, to prevent washing. The subsoil may also be plowed and in arid regions (dry land farming) it is packed after plowing so as to restore its capillary spaces. In some dry regions a crop is grown only every alternating year. The first year, the soil is plowed, and the surface is kept loose and porous so as to reduce the loss by evaporation; the second year the crop is grown.

The capillary condition of soils which are too loose and porous, and also those too heavy and compact, is improved by incorporating vegetable matter with the soil. Capillary conditions may also be improved by plowing of soil or subsoil when in suitable condition.

Under-drainage, by aerating the soils, allows roots to go deeper, and so places at their disposal a larger volume of soil containing plant food and water. Since an excess of water keeps the soil cold, drainage causes the land to warm up sooner in the spring.

Losses of water by evaporation may be prevented by tillage. Surface cultivation of the soil breaks up the capillary pores, and prevents water rising to the surface. The following table of King illustrates the effect:

	Water evaporated in 221 days. Inches
Compact soil	7.98
Stirred 1 inch	5.09
Stirred 2 inches	4.20
Stirred 3 inches	3.66
Stirred 4 inches	3.60

Compacting the soil by rolling increases evaporation, since it increases the efficiency of the capillary pores. Rolling after planting grass seed is often advantageous, as it brings moisture to the surface to sprout the seed.

The destruction of weeds prevents loss by evaporation. In

orchards it is often advisable to keep the soil cultivated and free from weeds or crops in order to prevent injury to the trees from want of water.

Wet and Dry Soils.—Dry soils are composed of coarse particles, with free percolation and little power of retaining water. Wet soils are composed of very fine particles having an enormous extent of intersurface and offering great resistance to the passage of water.

The character of the subsoil is also of great influence. A sandy surface soil acts differently when it has a subsoil of loam or clay. A clay soil is no longer wet when it has an open porous subsoil. Whether the soil is level or on a hill side or receives the drainage of higher land, influences the water held in the soil.

The most suitable physical composition of a soil depends on the climate and the situation in which it is placed; soils of great value in one situation may be of little value in another. A clay land which can be used only for pasture with an available rainfall of forty inches, may be used to great advantage where the rainfall is only twenty-five.

Effect of Cultivation and Manure.—Shallow surface cultivation conserves moisture. Rolling compacts the soil and causes water to rise to the surface. Fall plowing allows water to penetrate the soil, and if followed by surface cultivation, may allow a balance of water to be carried over to the next season. Spring plowing, if followed by dry weather, causes loss of moisture by evaporation; it should therefore be followed by surface cultivation. Manure or straw, spread as a mulch, prevents loss of water by evaporation.

CHAPTER VIII.

CHEMICAL CONSTITUENTS OF THE SOIL.

The soil is composed of disintegrated rocks, containing organic matter. Its constituents are, therefore, inorganic and organic. The inorganic constituents consist of the original rock minerals, products of their partial decomposition, and their final products of decomposition. The organic constituents consist of unchanged residues of plants and animals, intermediate substances formed by the action of bacteria, molds, and other agencies, and the final products of decomposition, namely, carbon dioxide and water.

Primary and Secondary Minerals.—By far the greater portion of the crust of the earth, and of the soils thereon, is composed of silica, and combinations of silica with bases, termed silicates. A large number of silicates are known, many of which are very complex in constitution. Igneous rocks, which are the oldest rocks, are composed entirely of silica or silicates. Primary silicates undergo chemical changes, under the action of the air, water, and other natural agencies, whereby other silicates and other minerals are formed. The unchanged minerals found in igneous rocks are for this reason termed *primary* minerals, and those produced from them by chemical agencies are called *secondary* minerals.

Soils are composed of three classes of minerals:

(*a*) Primary minerals, the unchanged minerals of igneous rocks, not easily affected by chemical reagents.

(*b*) Hydrated silicates, which are intermediate products of the decomposition of the primary minerals, and more easily acted on by chemical reagents and the roots of plants.

(*c*) Final products of weathering.

The relative abundance of these three classes of minerals in the soil will depend on the age and nature of the rock material and the nature and activity of the weathering agencies. Old soils are naturally more highly decomposed than are soils of more recent origin. Transported soils consist of a greater variety of minerals

than soils formed from rocks in place, and not mixed with the products of the decomposition of other rocks.

Primary Minerals.—Dr. F. W. Clarke,[1] Chemist to the U. S. Geological Survey, has calculated the relative abundance of the minerals of igneous rocks to be as follows:

	Per cent.
Feldspars	59 5
Hornblende and pyroxenes	16.8
Quartz	12.0
Biotite	3.8
Titanium minerals	1.5
Apatite	0.6
Less frequent minerals	5.8

Quartz is crystallized silicon dioxide (SiO_2) and is widely distributed in nature. It is insoluble in water or any acid except hydrofluoric. It is very hard and not easily broken. It cannot be dissolved or decomposed by natural agencies, although it may be reduced to a fine powder. It is often found as pebbles, sand, and sometimes a very fine powder, in residues from rocks which have otherwise undergone serious changes. It is of common occurrence in soils. It has no value to plants as food.

Felspars are double silicates of alumina with potash, soda, or lime. They are widely distributed, making up about sixty per cent. of the average igneous rock. The chief varieties of felspar are:

Orthoclase, a potash felspar	$KAlSi_3O_8$
Albite, a soda felspar	$NaAlSi_3O_8$
Anorthite, a lime felspar	$CaAl_2Si_2O_8$

A number of intermediate varieties occur, such as oligoclase, a soda-lime felspar.

Felspars are not acted upon by strong acids (except hydrofluoric) and can only be brought into solution after fusion with carbonate of soda, or by decomposition with hydrofluoric acid. They are slowly decomposed by weathering agencies. If finely ground felspar is brought in contact with water containing phenolphthalein, the liquid assumes a red color. This is due to the solution of a small amount of soda and potash, which, being

[1] Bulletin 419, p. 9.

alkaline, turn the phenolphthalein red. A number of other minerals behave in the same way. The quantity of alkali which goes into solution is, however, very small. Only a small fraction of felspar is dissolved by the concentrated hydrochloric acid used in soil analysis and about 1 to 4 per cent. of the total potash. The potash held in felspar has only a slight value to plants, as it is dissolved very slowly.

Micas are primary silicates, which are easily split into thin, flexible, and elastic leaves. They have a complex and varying composition, being silicates of alumina with potash, lithia, magnesia, iron or manganese. Muscovite is light colored potash mica, $K_2Al_6Si_6\ O_{22}2H_2O$. Biotite, a dark colored mica, is a complex hydrated silicate of alumina, iron, potash, and magnesia.

Micas are decomposed very slowly. They persist for a long time after the other rock minerals have been entirely changed by weathering. Almost any soil derived from granite contains flakes of mica, which are more easily seen if oxides of iron are removed with a little hydrochloric acid. Micas aid in the decomposition of rocks in which they are present, by allowing water to percolate into their fissures. Mica is, to a large extent, dissolved by strong acids, and it is probable that the plant food it contains is more easily used than that of felspar.

Hornblendes and Pyroxenes include a number of silicates of varying composition, though with related properties. They are complex silicates of magnesia, alumina, lime, and iron. They are usually green, brown, or black in color. They are easily affected by natural agencies. Olivine is a silicate of iron and magnesia $(MgFe)_2Si_2O_4$.

Apatite $Ca_3PO_4Ca(ClF)_2$ is a crystallized phosphate of lime. It is considered to be the chief form in which phosphoric acid occurs in igneous rocks.

Secondary Minerals.—The minerals formed from the primary minerals by processes of combination with water, by solution, oxidation, or by partial or complete decomposition, are termed *secondary* minerals. They occur in rocks formed by decomposition of the igneous rocks, and in soils. A few of them are described in the following paragraphs.

Hydrated Silicas are formed by the deposition of silica from aqueous solutions. From many silicates water dissolves silica, which may be deposited as various forms of hydrated silica. Hydrated silicas are probably present in some soils.

Hydrated Silicates are produced by combination of water with primary or secondary silicates, with or without loss of matter by solution. The complex hydrated silicates are more easily decomposed, and otherwise enter into reactions much more readily than the primary silicates, from which they were formed. They are also more easily decomposed by acids. Hydrated silicates appear to be of considerable importance in the soil. A great number of hydrated silicates are known.

Zeolites are hydrated silicates of alumina, with varying amounts of potash, soda, lime, etc., produced by hydration and decomposition of many varieties of minerals. They are easily decomposed by acids. A large number of zeolites are known. They take part in some important reactions which occur in the soil, especially the fixation of potash.

Chabazite $(HK)_2CaAl_2Si_5O_{15}+6H_2O$, stilbite $(CaNa)_2Al_2Si_6O_{16}+6H_2O$, analcite $Na_2Al_2Si_4O_{12}+2H_2O$ and prehnite $H_2Ca_2Al_4Si_3O_{12}$, are hydrated silicates belonging to the zeolite class. They are soluble in hydrochloric acid, the silica being separated. When brought in contact with salts of potash, they remove some of the potash from solution and replace it with equivalent quantities of lime or soda. For example, the minerals named below[1] were treated with a strong solution of sulphate of potash, washed and subjected to analysis:

	Original mineral	After treatment
	Per cent. potash	Per cent. potash
Stilbite	0.25	3.95
Stilbite, another sample	0.17	4.09
Analcite	0.47	1.54
Chabazite	0.90	4.82
Chabazite, another sample	1.00	5.96

[1] Texas Station, Bulletin 106, p. 11.

The reaction may be represented as follows:

Chabazite + K_2SO_4 = K Chabazite + $CaSO_4$.

The reaction is reversible. When treated with sulphate of lime, or other lime salts, the absorbed potash is partly replaced by lime.

K Chabazite + $CaSO_4$ = K_2SO_4 + chabazite.

The extent of the change depends on the conditions of the experiment and will be discussed under the topic of fixation by the soil. It is possible that other hydrated silicates besides zeolites take part in the fixation of potash.

Pinite is a hydrated silicate of alumina and potash, resulting from the decomposition of felspar and some other minerals.

Kaolinite is a hydrated silicate of alumina having the formula $Al_2Si_2O_7 2H_2O$. Kaolin is largely composed of kaolinite. Clay contains kaolinite. Kaolin may be considered as a final product of weathering of felspar and other silicates containing alumina. The reaction which occurs in the formation of kaolin by the action of water containing carbon dioxide upon felspar, may be written as follows:

$K_2Al_2Si_6O_{16} + H_2O + CO_2 = Al_2Si_2O_7 + K_2CO_3 + H_2Si_4O_9$.

If lime or soda is present, its carbonate is formed in this decomposition. The lime or soda may be converted into sulphate or chloride if sulphur or chlorine is present in the rock.

Chlorites are hydrated silicates of alumina, magnesia, or iron. They are products of the decomposition of hornblende, augite, and magnesium micas. Further decomposition results in *serpentine.*

Talc and *Serpentine* are hydrated silicates of magnesia. They are soft, with a greasy feeling. Serpentine results from the decay of olivine, and, though less often, from augite or hornblende.

Glauconite is a hydrated silicate of alumina and iron, containing a small quantity of lime, magnesia, potash, soda, and phosphoric acid. It often occurs as grains of a green color, and is termed green sand. Green sand marl is a mixture of glauconite and calcium carbonate.

Carbonates of Lime and Magnesia result from the action of

carbon dioxide and water upon many silicates containing lime and magnesia. Both compounds are slightly soluble in water, and more soluble in water containing carbon dioxide. All waters which have been in contact with the earth contain lime and magnesia. Large limestone deposits have been formed by shell fish and other organisms, which withdraw carbonate of lime from solution. Many of our most fertile soils are derived from limestone deposits, or contain two per cent. or more of carbonate of lime. Carbonate of lime is an important soil constituent. Its presence flocculates clay and makes clay soils less sticky and more easily worked. In calcareous soils, the phosphoric acid and potash is generally held in more available forms. Carbonate of lime unites more or less slowly with soluble phosphates which may be present or introduced into the soil, forming compounds which, while less soluble than before and of less value to plants, are more soluble and apparently of greater value to plants than the soil compounds of phosphoric acid with iron or aluminium. Other actions of lime will be referred to later.

Sulphate of lime is found in small quantities in many soils, in large quantities in a few soils.

Iron Minerals.—By the decomposition of silicates containing iron, various compounds of iron are produced, mostly oxides and carbonates. These bodies ordinarily occur in the soil, often giving the soil a red, brown, or yellow color, depending on the stage of oxidation. Hematite is anhydrous ferric oxide Fe_2O_3, red when finely powdered. Magnetite Fe_3O_4 is black oxide of iron. Limonite is hydrated ferric oxide $2Fe_2O_3 3H_2O$, and has a yellow or brown color. Siderite is carbonate of iron, and is gray or brown in color. It is affected with difficulty by cold acids, easily by hot acids. The bulk of the phosphoric acid of ordinary soils is probably in combination as basic phosphates of iron or aluminium, or in basic silicates of these elements. Such forms of combination are apparently not as valuable to the plant as the calcium phosphates. Limonite is deposited from water containing iron. Oxides of iron are reduced by decaying vegetable matter and combine with carbonic acid to form ferrous car-

bonate, which dissolves in water. On exposure to the air, the ferrous carbonate is oxidized and is precipitated as insoluble hydrated ferric oxide. This action does not take place in soils containing carbonate of lime. A layer of hard pan, consisting of rock grains cemented by limonite, is often formed below poorly drained soils.

Pyrite FeS_2 has a light yellow color and is often called fool's gold. It is easily oxidized to sulphates by atmospheric agencies. It is sometimes formed in badly aerated soils.

Phosphate Minerals.—Phosphates do not, as a rule, occur in large quantities in the soil, but are important on account of their indispensability to plant life. The important phosphate minerals are: Apatite, or crystallized calcium phosphate $Ca_3(PO_4)_2$; phosphate rock, or amorphous calcium phosphate; vivianite, which is hydrated phosphate of iron; wavellite, or hydrated phosphate of alumina. The three phosphates named last probably occur in soils. A large number of mineral phosphates are known. Dr. F. W. Clarke, of the U. S. Geological Survey, assumes that all the phosphoric acid of igneous rocks is present as apatite. As stated above, phosphates are also found in the soil as basic compounds of iron and aluminium. Organic phosphorus compounds are also present in the soil.

Soluble Salts.—Sulphate of soda, or glauber's salt, sulphate of magnesia, chloride of soda, carbonate of soda and nitrate of soda may be found as constituents of soils in arid sections, and, if present in excessive quantity, are detrimental to vegetation and give rise to alkali soils.

Investigations of the Mineral Constituents of Soils.—Studies of the mineral constituents of the soil[1] are made by means of microscopic examination with the aid of polarized light, stains, and other tests. Comparatively few mineralogical studies of the soil have been made. They are sufficient, however, to show that there are considerable differences in the mineral content of soils, particularly of those widely different origin.

Chemical examination also throws some light upon the mineral

[1] Bull. 91, Bureau of Soils.

composition of the soil. The quantity and character of the substances brought into solution by means of various solvents, may be compared with the effect of the same solvents under the same conditions upon minerals in the proportions in which they may occur in soils. For example,[1] known phosphates of lime are completely dissolved by fifth normal nitric acid under certain conditions; some phosphates of iron and aluminium are also completely dissolved, while basic phosphates of iron and aluminium are dissolved by the solvent only to a slight extent. Hence treatment of the soil with this solvent gives an idea as to the condition of the inorganic soil phosphates. This matter will be discussed later.

Hilgard[2] determined the alumina dissolved and the silica which was liberated by strong acids, and by comparing the relative quantities, came to the conclusion that the quantity of silica was not sufficient to combine with the alumina to form known silicates, and that a portion of the alumina in certain soils is present as hydrated alumina, probably Gibbsite $Al(OH)_3$.

Organic Matter.—The organic matter and nitrogen of the soil are closely related, for nitrogen is chiefly in organic combination. The organic matter of the soil consists of the residues of plants and animals, animal excrements, and the products of their decay. All the compounds which are found in plants or animals, enter the soil, through the presence of some of them is very transitory.[3] Sugars, urea, and similar substances, are rapidly changed into other bodies. Cellulose and lignin, which make up the woody matter of plants, decay much more slowly, and may remain in the soil for some time. Lactic, acetic, and butyric acids are produced in the fermentation of sugars and starches. Vegetable acids, such as oxalic, citric, tartaric, and malic acid are introduced into the soil in plant residues, but are quickly destroyed by bacteria. Proteids and fats persist for a longer or shorter time, according to their nature. It is thus possible for all the organic compounds found in plant or animal residues to be present, in

[1] Texas Station Bulletin 126.

[2] The Soil, p. 389.

[3] Wollny, Die Zersetzung d Org. Stoffe.

greater or less quantity, in the soil, and the student of soil chemistry must bear this possibility in mind.

Organic Compounds Isolated.—Chemical study of the organic matter of the soil has rendered probable the existance of a number of organic bodies in the soil. The organic compounds claimed to be isolated, so far, make up only a comparatively small percentage of the total organic matter.

Schreiner and Shorey[1] claim to have isolated sixteen compounds.

Hydrocarbons.—Hentriacontane C_3H_{64} from a North Carolina soil.

Acids.—Dihydroxystearic acid $C_{18}H_{36}O_4$ and picoline carboxylic acid $C_3H_7O_2H$ from several soils. Paraffinic acid $C_{24}H_{48}O_2$, and monohydroxystearic acid $C_{18}H_{36}O_3$, lignoceric acid $C_{24}H_{48}O_2$, agroceric acid $C_{21}H_{42}O_2$ and resin acids from individual soils.

Glycerides.—Glycerides of fatty acids identified in one soil and probably present in several soils.

Wax Alcohols.—Phytosterol $C_{26}H_{44}O.H_2O$ and agrosterol $C_{26}H_{44}O.H_2O$ from individual soils.

Nitrogenous Compounds.—These are chiefly bases, and form salts with acids. Arginin, cytosine, xanthine, and hypoxanthine, were claimed to be isolated from several soils.

Pentosans.—The presence of pentosans in the soil was demonstrated by de Chalmot[2] and others and confirmed by Schreiner and Shorey. In ten soil samples, pentosan carbon made up 1.30 to 28.5 per cent. of the total carbon.

Ether Extract.[3]—The soil gives up about 0.02 per cent. material to ether, and about the same quantity to chloroform following the ether. The ether extract consists of fatty acids and wax alcohols, such as are found in plants.

Significance of the Organic Compounds.—As stated above, the organic compounds mentioned make up only a very small fraction of the total organic matter of the soil. The bulk of the organic mat-

[1] Bulletins 53 and 74, Bureau of Soils.

[2] Am. Chem. Jour., 1894, p. 229.

[3] Texas Bulletin, 157.

ter is made up of so-called humus, which will be discussed later. There is still much room for investigation in distinguishing various chemical compounds in the soil. Some of the organic compounds mentioned above have been found in only one or two soils, while others are perhaps of general occurrence. Most of them appear to be indifferent toward plants, and their significance towards plant growth or soil chemistry is not known. The importance of these substances is at present chiefly due to their relation to the toxic theory of soil fertility.

The Toxic Theory.—According to the toxic theory of the Bureau of Soils, "the production of toxic excretions by the roots of plants is undoubtedly a factor in soil fertility."[1] "So-called exhausted soils are poisoned soils."[2] "Practically all soils contain sufficient plant food for good crop yields—and—this supply will be indefinitely maintained."[3] "The small yields of unproductive soils can be greatly improved by treatments which destroy toxic substances in these soils."[4] "The soil is the one indestructible immutable asset that the nation possesses. It is the one resource that cannot be exhausted, that cannot be used up."[5]

The evidence offered in support of this theory is based chiefly upon experiments in water cultures and wire-basket tests of about three weeks duration. The aqueous extract from an unproductive soil grew larger wheat plants when ferric hydrate, calcium carbonate, or carbon black were added to it.[6] Pure water is better suited for growing wheat plants than is the soil extract of poor soils.[7] The extracts of the poor soils are benefited by nitrate of soda, carbon black, pyrogallic acid and tannic acid, and the same chemicals have similar effects when added to the soil.[8] Dihydroxystearic acid and picoline carboxylic acid isolated

[1] Bulletin 40, p. 40.
[2] Bulletin 28, p. 28.
[3] Bulletin 22, p. 63 4.
[4] Bulletin 47, p. 51.
[5] Bulletin 55, p. 66.
[6] Bulletin 28.
[7] Bulletin 36.
[8] Bulletin 36.

from soils kill wheat seedlings at dilutions of 100 parts per million, and are injurious in lower amounts.[1] Fertilizers decrease the injurious effects of certain organic substances.[2]

Dauheney,[3] at Oxford, England, tested the old toxic theory of De Condalle by a rotation experiment, in which 18 different crops were grown continuously on the same plots in comparison with the same crops grown in various rotations; the yields were not sufficient to justify the assumption of the existence of a toxin. Russell[4] grew six crops of rye in succession on sand containing

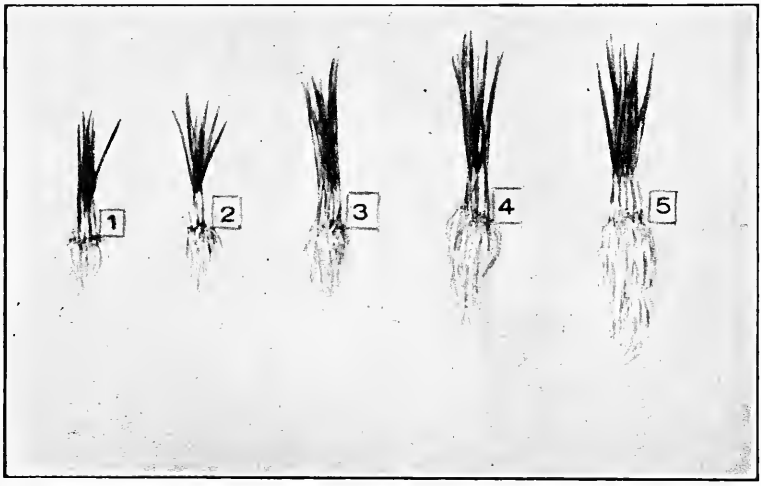


Fig. 37.—Wheat seedlings ten days old grown in water containing dihydroxystearic acid (1) 200 parts per million; (2) 100 parts; (3) 50 parts; (4) 20 parts; (5) 0 parts. Bureau of Soils.

nutrient salts. A seventh crop grown on this sand, and another crop on fresh sand, were practically equal in size. Other experiments with rye on soil, and with buckwheat and spinach on sand and on soil, give practically the same results. Hence there is no evidence that the previous crops left toxic residues.

[1] Bulletin 47.

[2] Bulletin 70.

[3] Phil, Trans., 1845, p. 179.

[4] Soil Conditions and Plant Growth, p. 111.

Russell[1] states that single salts of potassium, magnesium, sodium, etc., are toxic to plants, in water culture, while a mixture of salts is not. Breazeale and Le Clerc[2] show that wheat seedlings grown in culture solutions containing 10 parts per million of potassium chloride or potassium sulphate, cause the solution to become acid. The acidity affects injuriously the development

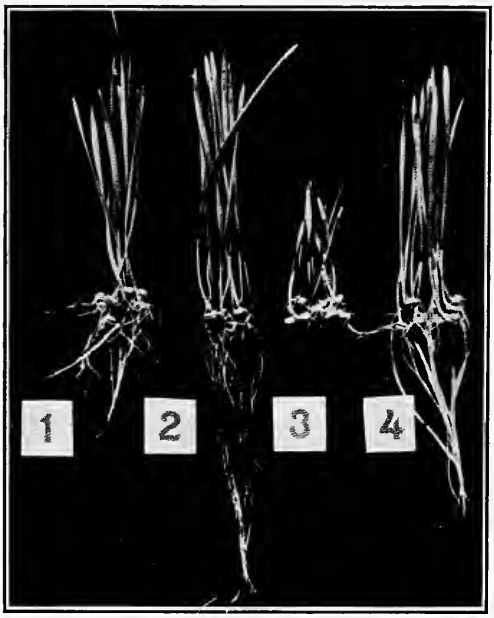


Fig. 38.—Wheat seedlings (second crop) grown in, (1) distilled water, (2) distilled water and calcium carbonate, (4) potassium sulphate and calcium carbonate, compared with (3) those grown in potassium sulphate solution.

of succeeding plants grown in the solution, and a similar effect is shown by solutions of sulphuric acid or hydrochloric acid. Sodium hydroxide, lime, ferric hydrate or carbon black, remove the acidity and render the solution less injurious.

[1] Soil Conditions and Plant Growth, p. 43.

[2] Bulletin No. 149, Bureau of Chemistry.

There is thus not sufficient experimental evidence to support the theory that low yields are ordinarily due to toxic substances in the soil, rather than to deficiency of plant food. The injurious effects observed in the water culture experiments may be due to acidity. It is, of course, possible that some soils may contain organic toxic substances other than acids, but this fact has not been established.

Assimilation of Organic Compounds by Plants.—Experiments have been made to ascertain whether organic compounds may be assimilated by plants. The organic compounds most important are those which may enter in the soil in animal excrements or plant or animal residues, or may be formed in the decay of these. Uric acid and urea are found in urine, hippuric acid occurs in the urine of cows, sheep, etc., leucin, tyrosin and asparagin, are found in plants or formed in their decay. Other organic bodies formed in the decay of plants or animals, are probably of little importance.

The question as to the assimilation of these substances as such is complicated by the fact that they are for the most part easily transformed into ammonium salts, which may be assimilated.

Baeyer found oats to grow well in a solution of urea, and the plants contained considerable amounts of urea. But ammonia had formed in the solution. Hampe[1] grew corn with urea and found the leaves to contain 0.25 to 0.81 per cent. urea. The solution was changed every day to avoid error by decomposition, and, though the corn possibly assimilated some ammonia, the evidence is that it utilized urea also. A. Thomson[2] compared sodium urate, sodium hippurate, urea, and sodium nitrate, on oats and barley in water cultures, and found that uric acid and urea have the same value as nitric acid, but hippuric acid has not. This investigator did not correct for decomposition of the compounds. Other experiments[3] could be quoted tending to prove that leucin,

[1] Landw. Versuchs-stat., 1867, p. 79.

[2] Exp. Station Record 13, p. 919.

[3] Hutchinson and Miller, Jour. Agr. Sci., 1912, p. 283, references being given.

tyrosin, asparagin, and hippuric acid can serve directly as sources of nitrogen for cultivated plants. Hippuric acid is decomposed into glycocoll and benzoic acid, the glycocoll taken up and the benzoic acid left behind. It is also claimed that humic acid[1] can be absorbed.

Humus.—The term *humus* is applied by some chemists (principally in European countries) to the entire quantity of organic matter in the soil, in whatever form it may be present. In America, it usually refers to the organic matter dissolved by ammonia after the lime has been removed by acids. This ammonia-soluble organic matter is supposed to be more valuable than that not soluble in ammonia, though satisfactory evidence that such is the case has not been presented.

Ammonia-Soluble Organic Matter.—In the preparation of the ammonia-soluble organic matter, the lime is first extracted with acid and the soil washed free from acid. The soil is then treated with ammonia, but a quantity of clay is also suspended in the liquid. The clay is precipitated by addition of ammonium sulphate, ammonium carbonate, or other salts, and the ammonia neutralized. The precipitate is collected and washed thoroughly. The precipitated substance is a black, amorphous body, slightly soluble in water. It has acid properties. It decomposes calcium carbonate, liberating carbon dioxide. A portion of it is soluble in alcohol.[2] It is soluble in ammonia, and when the excess of ammonia is evaporated, retains 4 to 6 per cent. nitrogen in the form of an ammonium salt. It is precipitated by salts of lime, barium, copper, zinc, lead, etc., forming salts of these metals. Its combining weight varies from 228 to 327. The magnesium salt is soluble in water, and also the sodium, potassium and ammonium salts. When dissolved in ammonia, a portion of the humate diffuses through parchment paper.

Analysis of the substance prepared from several soils by

[1] Brial, Exp. Sta. Record 6, p. 484.

[2] Fraps and Hamner, Texas Bulletin 129.

precipitation with acid from ammonia solution, gives the following results:[1]

	Per cent.
Carbon (usually about 55 per cent.)	44.09–63.58
Hydrogen	3.27– 5.45
Nitrogen	3.36– 6.22
Ash	1.57–15.74

The substance is probably a mixture and not a single definite compound.

According to Hilgard and Jaffa,[2] the humus of humid soils (extracted with caustic potash) contains about 5 to 5.5 per cent. of nitrogen, while that of arid soils may contain as much as 18.5 per cent. nitrogen. Hilgard believes that the nitrogen content of humus should not fall below 4 per cent., if the soil is to be productive.

Attempts have been made to separate definite chemical compounds from humus, the success of which is doubtful. Detmer[3] extracted humus from the soil with ammonia, and after repeated purifications obtained a compound said to be of the formula, $C_{20}H_{18}O_9$. It was a black acid substance which reddens litmus, expels carbonic acid from carbonates, and forms salts with lime, silver, iron, ammonia, potassium, etc. These salts are all insoluble with the exception of salts of the alkalies. Other acids in addition to this one are claimed to have been separated from the soil. There is doubt, however, whether the bodies in question are really definite chemical compounds or more or less impure mixtures.

There is no evidence that the ammonia-soluble humus of the soil consists entirely of acids, or that it is formed by decomposition in the soil. Various bodies known to be non-acid are found in

[1] Fraps and Hamner, Texas Station Bulletin 129.

[2] Rep. Cal. Exp. Sta., 189, p. 2-4.

[3] Jahresber, f. Agr. Chem., 1870-2, p. 68.

plants, such as proteids and lignin, and are soluble in ammonia.[1] No doubt they also occur in the soil. In attempts to determine the formation of humus in the soil, these ammonia-soluble materials introduced with the ingredients have been neglected. In experiments[2] in which the ammonia-soluble organic matter originally in the soil and that added to it, were estimated before and after decomposition for several months, there was a loss, and not a gain, of ammonia-soluble material. The following is an example:

Percentage of humus in original soil	1.36
Dry soil with meat	2.29
Soil with meat moist for 14 weeks	1.68

Estimation of Ammonia-Soluble Humus.—In the estimation of ammonia-soluble humus,[3] the soil is first extracted with 1 per cent. hydrochloric acid, to remove lime and decompose the compounds of humic acid. It is then washed free from acid, and treated with 4 per cent. ammonia for some time. After remaining in contact for several days, the solution is allowed to settle, and an aliquot part evaporated to dryness, dried and weighed, ignited and weighed again. The loss in weight is ammonia-soluble humus.

This method is highly inaccurate on account of the presence of clay. Clay will remain in suspension in ammonia-water for months, and, as it contains chemically combined water, will lose weight on ignition, after drying. It is also present in the humic acid precipitated with the solution, unless previously removed. The clay may be easily removed by precipitation with ammonium carbonate.[4] The ammonium carbonate is volatilized along with the ammonia when the solution is subsequently evaporated to dryness.

Humus of Peat and Swamps.—As we have already stated, acid bodies are formed in peat and muck soils, which must be neutralized by lime before the soil can be cultivated profitably. It

[1] Hoffmeister, Landw. Versuchs-stat., 1898, p. 347.

[2] Fraps and Hamner, Texas Bulletin 129.

[3] Methods of the Association of Official Agricultural Chemists.

[4] Rather, Bulletin 139, Texas Station.

is also possible that the lime, by combining with the peat resin, causes the peat and muck to oxidize more rapidly.

Certain investigators claim to have separated ulmic acid, crenic acid, and other acids from peat.

Importance of Humus.—The functions of the organic matter in the soil may be summed up briefly as follows:

1. It contains the store of nitrogen of the soil.

2. It furnishes nutriment for bacteria and other forms of life, which aid in changing plant food so that the plant can take it up.

3. It produces carbon dioxide and other acids in its decay, which increase the solvent action of the soil water on plant food.

4. It increases the retentiveness of sandy soils for water, and binds the fine particles of clay into compound particles, so that the clay has better tilth.

5. Like lime, an abundance of humus renders a soil productive even though only small quantities of plant food are present.

Classification of Soils with Respect to Humus.—Knop[1] makes the following divisions, using the term humus to mean the entire quantity of organic matter present:

	Per cent.
Poor in humus	0.0 to 2.5
Fair	2.5 to 5.0
Good	5.0 to 10.0
Rich	10.0 to 15.0
Excess	15.0 and over

The humus in the soil decreases from the surface. The following analyses by Kosticheff of the black soil of Russia illustrates this:

Depth inches	Percentage of humus
1 to 6	5.4
6 to 12	4.8
12 to 18	3.6
18 to 24	2.6
24 to 30	2.6
30 to 36	1.9
36 to 42	1.3

[1] Quoted by Wollny, Zersetzung d Orgnanischen Stoffe, p. 192.

Ammonia-Soluble Phosphoric Acid.—The ammonia-soluble phosphoric acid of the soil is assumed by some chemists to be in combination with the organic matter which accompanies it, and to be of considerable value. It comes in part, however, from inorganic phosphates which occur in the soil and are decomposed by ammonia, allowing a portion of their phosphoric acid to go into solution.[1] The humic acids precipitated with acids contain a small portion of the ammonia-soluble phosphoric acid, and this is probably in organic combination. The quantity of phosphoric acid held in this way is small, even in soils richly supplied with humus. It cannot be taken up until released by oxidation of the humus, and can only be regarded as a reserve store of phosphoric acid, not nearly so important as the nitrogen held in the humus in much larger proportion.

[1] Fraps, Am. Chem. Jour., 1898, p. 574; Bulletin 135, Texas Exp. Sta.

CHAPTER IX.

CHEMICAL COMPOSITION OF THE SOIL.

Chemical analysis shows that the greater bulk of the soil is composed of compounds of silica, oxides of iron, and oxides of alumina, in various compounds. These substances have no value as plant food, except iron, and only very small amounts of it is essential. They serve a useful purpose, however, in holding moisture, modifying the supply of plant food, supporting the plant, and, giving it a medium in which to develop its roots.

The important plant foods—nitrogen, phosphoric acid, and potash— make up only a small percentage of the soil. The quantity of plant food may be large in pounds per acre, sufficient for several hundred crops, if it were all available for use of the plant. But the proportion of plant food to the total quantity of soil is small. Further, the amount which can be taken up by plants may be only a small proportion of the total amount present; so that although several hundred pounds of phosphoric acid, for instance, may be present in the soil, the addition of a few pounds of highly available phosphoric acid may produce a large increase in the crop.

Methods of Examination.—Four chief methods of examining soils have been used. In addition, special methods are used for special analyses.

(1) Complete decomposition of the silicates. This method gives the total quantity of the constituents of the soil.

(2) Partial decomposition with strong acid. This method attempts to determine the quantity of plant food which may become available to the plant in a series of years. It distinguishes between the most resistant silicates, and those decomposed by acids.

(3) Weak Solvents. This method attempts to determine the immediate needs of the soil for plant food.

(4) Water-Soluble Constituents. This method considers the material extracted from the soil by water.

Complete Decomposition.—The complete analysis of the soil is made in two ways:

First Method.—The soil is fused with a mixture of sodium carbonate and potassium carbonate. The silica unites with the soda or potash, forming silicates; oxides or carbonates are formed from the bases. On treatment with water and acids, the carbonates and oxides dissolve. The silica can easily be separated and the bases determined in the solution. If potash or soda is to be estimated, they must be brought into solution by some other method, such as that named below, or by fusing the silicate with lime.

Second Method.—The soil is treated with hydrofluoric acid, until the silicate is completely dcomposed and the silica driven off as gaseous silicon fluoride SiF_4. The residue is then dissolved in acids, and subjected to analysis. The estimation of the silica, if desired, is accomplished by the first method.

Complete decomposition of a soil shows the constituents which are locked up in the most refractory silicates, as well as those which are easily affected by plants. So far as the writer has been able to find, there have been no investigations made as to the relation of the complete analysis of the soil to its wearing qualities, or needs for plant food. The utmost information such analysis provides at present, is the amount of plant food which may some day become available.

The complete analysis of some groups of soils is shown in the following table, compiled from Bulletin No. 54 of the Bureau of Soils:

Complete Composition of Some Soil Groups, Per Cent.

	No. averaged	P_2O_5	CaO	MgO	K_2O
Coastal plains	7	0.07	0.16	0.16	1.77
Residual	3	0.18	0.67	0.76	2.08
Glacial	10	0.22	1.35	0.80	2.09
Limestone and shale	5	0.27	—	0.86	2.80

Relation to Sizes of Particles.—Chemical analysis of the different grades of particles have not always given the same result, but

as a rule, the percentages of alumina, potash, and lime increases as the size of the particles decrease. For example, Failyer[1] determined phosphoric acid, lime, magnesia, and potash in separate grades of particles from a number of soils of the United States by the method of complete decomposition. In the following table is given the average percentage of three ingredients of the sand, silt, and clay of four groups of soils:

	Phosphoric acid			Lime			Potash		
	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
7 Coastal plains soils	0.03	0.10	0.34	0.07	0.19	0.55	0.37	1.33	1.76
3 Residual soils	0.07	0.21	0.67	0.50	0.82	0.94	1.60	2.37	2.86
10 Glacial soils	0.15	0.23	0.86	1.24	1.30	2.68	1.72	2.35	3.08
5 Limestone and shale soils	0.04	0.07	0.16	1.80	1.88	2.85	0.18	1.02	0.84

It is seen that the finer particles of the soil are, on an average, richer in phosphoric acid, lime, and potash than are the coarser particles. The percentage of each of the constituents named increases with the fineness of the particles, the only exception in the table being the potash in the clay of the limestone and shale soils. The relative abundance of the various grades of particles would determine the quantity which each contributes to the soil. The coastal plains soils have been so weathered and leached, that they are lower in phosphoric acid, lime, and potash than the less extensively weathered residual soils, and these in turn are lower than the glacial soils, which consist largely of crushed rocks, many of which have not been weathered to a great extent.

Analysis by Extraction with Strong Acids.—This is the method usually employed in the analysis of the soil. It consists in treating the soil with strong acid and estimating the constituents which go into solution. The extent of the solvent action depends upon the nature of the soil, the kind of acid, strength of acid, temperature, time of contact, and ratio of soil and acid. The methods used by different chemists vary. In the methods of the Association of Official Agricultural Chemists of North America

[1] Bulletin 54, Bureau of Soils.

10 grams soil are digested with 100 cc. hydrochloric acid of 1.115 specific gravity for 8 hours at the boiling temperature. Dr. E. W. Hilgard digests the soil on the steam bath for *five days*, a method which appears to give nearly the same results as the official method, with the exception of potash, and oxides of iron and alumina. In the one comparison made by Dr. Loughridge,[1] 0.35 per cent. potash was dissolved by the one method, and 0.63 per cent. by the other, or nearly twice as much. This difference must be considered in comparing the analyses made by Hilgard's method with the analyses made by the methods of the Association of Official Agricultural Chemists.

The proportion of the constituents of the soil which are dissolved by strong hydrochloric acid varies considerably with different soils. For example, Veitch[2] determined in 16 Maryland soils the total quantity of each constituent and the quantity dissolved by strong acid by the A. O. A. C. method. The results are presented in the following table, expressed in percentage of the total quantity of each ingredient present:

PERCENTAGE OF TOTAL PHOSPHORIC ACID, ETC., DISSOLVED BY STRONG ACIDS.

	Average	Minimum	Maximum
Phosphoric acid	61	32	100
Potash	17	5	33
Lime	35	10	77
Magnesia	56	10	100
Alumina	54	24	100
Oxide of iron	82	57	100

The average order in which the constituents of these soils were dissolved was as follows, beginning with the most soluble: oxide of iron, phosphoric acid, magnesia, alumina, lime, and potash. On an average, only 17 per cent. of the total potash of the soil was dissolved by the A. O. A. C. method. None of the soils in question were highly calcareous, otherwise a much greater proportion of lime and magnesia would have been dissolved.

[1] Hilgard, The Soil, p. 341.

[2] Maryland Bulletin No. 70.

Relation of Composition to Fertility.—The relation of the composition to the fertility of the soil is studied by comparing the chemical analysis with the productiveness of known soils.

Soils containing comparatively high quantities of plant food are generally very productive and durable, under favorable physical conditions. The following table shows the composition of some very productive soils.[1] These soils are all well known for their fertility and wearing qualities.

PERCENTAGE COMPOSITION OF FERTILE SOILS.

	California Arroyo Grande Valley	Mississippi Yazoo Bottom	Texas Rio Grande Bottom	Russia Tchernozen
Phosphoric acid	0.71	0.30	0.20	0.14
Nitrogen	0.67	—	—	—
Potash	0.67	1.10	1.31	0.72
Lime	2.11	1.35	14.43	1.51
Magnesia	2.26	1.67	1.53	0.73
Carbon dioxide	1.82	—	9.91	—
Sulphur Trioxide	0.22	0.02	0.04	0.07
Alumina	7.40	10.54	9.11	5.22
Oxide of iron	5.23	5.82	4.09	7.12
Insoluble and soluble Silica	72.43	71.77	—	61.59
Loss of ignition	6.63	7.37	—	22.78
Moisture	—	—	—	—

The Arroyo Grande Valley soil is considered one of the richest soils in the world. The other soils mentioned in the table are all productive and durable. The analyses were made by Hilgard's method. Soils containing about 1 per cent. lime, 0.15 per cent. phosphoric acid, and 1 per cent. potash, by Hilgard's method, may be regarded as highly fertile. The same standards apply to the Association method, excepting it is possible that 0.50 per cent. potash is sufficient for a fertile soil. This, however, remains to be demonstrated.

When soils contain only small quantities of plant food, they will usually be found deficient in plant food for crops, or become so in a comparatively short time after being placed in cultivation. It appears probable that the plant food which can be taken up by

[1] Hilgard, The Soil, p. 343.

plants is, to a large extent, proportional to the total quantity present, though this depends on the changes going on in the soil.

A comparatively small amount of plant food in the soil is sufficient to make it productive, if present in an available form. If we assume the weight of one acre of soil to the depth of one foot to be 3½ million pounds, then 0.01 per cent. corresponds to 350 pounds per acre foot. A crop of 40 bushels of corn, including ears, stalk and leaves, requires about 25 pounds phosphoric acid, which would be about 0.0007 per cent., or 7 parts per million. Consequently as much as 0.01 per cent. phosphoric acid could supply 14 crops of corn of this size, if the plant could get it. But soils containing only this quantity of phosphoric acid usually respond to applications of phosphoric acid greatly.

The analysis by strong acids does not differentiate between compounds which may have different values to crops. Hence two soils may have the same composition but react differently to fertilizers. The chemical composition as determined in this way, is more closely related to the wearing qualities of the soil than to the immediate needs of the soil for plant food.

Number of Crops the Plant Food Will Supply.—This depends on the size and kind of crop, as well as on the composition of the soil. Assuming the entire removal of a crop of 40 bushels corn per acre, the following is the number of crops which could be supplied by the acid-soluble phosphoric acid and potash, and the total nitrogen in some Texas soil types,[1] if they were in such forms that they could be used by the crops without any loss.

Corn	Number of crops the plant food will supply		
	Phosphoric acid	Nitrogen	Potash
Norfolk soils	28	29	100
Orangeburg soils	70	35	308
Lufkin soils	28	29	91
Susquehanna soils	42	41	183
Houston soils	84	82	290
Yazoo soils	154	56	325

[1] Bulletin 126, Texas Station; see also No. 99.

Interpretation of Partial Soil Analyses.—The chemical analysis of a soil must be considered in connection with a knowledge of its location, depth, drainage conditions, permeability to water and air, and, if possible, the amount of crops it produces. Without consideration of the other factors which influence the fertility of a soil, the chemical analysis may not lead to satisfactory conclusions. We must also remember that the same general type of soil varies somewhat in composition, physical properties, and productiveness within a given area, and also that different methods of farming may cause considerable differences in soils originally the same.

The interpretation of a chemical analysis unaccompanied by knowledge of the other soil conditions which affect its fertility, may be unsatisfactory in a large proportion of cases. A careful interpretation of results with the aid of the knowledge referred to may sometimes be disappointing, but it is more often correct. Analyses of miscellaneous samples of soils is also of less value than systematic studies of definite areas. Analyses of virgin soils, or soils which have not been long under cultivation, or not treated with fertilizers, are more likely to yield a satisfactory interpretation than analyses of soils whose properties have been modified by long continued cultivation, or by applications of fertilizers. It cannot be expected that chemical analysis of soils will always give a satisfactory interpretation; there will be exceptions which may be difficult to understand until the scope of our information has been widened.

Chemical analysis of a soil with strong acids, together with other information concerning the soil, should aid us in applying the results secured by field experiments in one locality on a given type of soil, to other localities and to other types of soil. It is well known that the results of field experiments with fertilizers are applicable only to the same types of soils under similar conditions and with similar chemical composition, and may, or may not, be applicable to other types of soils. Chemical analysis, and the other information referred to, should aid us in applying knowledge secured by field experiments and by experience, to the

same type of soils located in different sections, and even to different types of soil from those under experiment.

The analysis of a soil with strong hydrochloric acid does not show exactly what fertilizer to apply to it, but it does give indications (*a*) as to the wearing qualities of the soil, (*b*) what elements are likely to become deficient first under a given system of cropping, (*c*) what deficiencies already exist in the soil, or will soon be brought out.

Virgin soils containing high percentages of plant food are highly productive unless improper physical conditions interfere with the welfare of the plant. Low percentages of plant food do not necessarily indicate low production when first put in cultivation. To use Hilgard's illustration, suppose a heavy alluvial soil of high plant food content is diluted with its own weight of sand. By improving the physical condition of the soil an increased crop will very likely result, though the percentage of plant food has been reduced by half. The root system of the plant in the diluted soil will probably be better developed and in more intimate contact with the soil particles, than in the undiluted soil. We may continue the dilution, using say 4 parts of sand to one of soil, 6 parts of sand to one of soil, and so on. At some point, the size of the crop will begin to decrease on account of the difficulty of securing plant food. How far the dilution may be carried depends upon the plant and on the soil, and is a subject worthy further study.

Standards for Interpretation.—Varying methods of analysis for soils, and varying standards of interpretation are used according to the method of analysis and the individual opinions of the analysts as to what constitutes a good soil. The standards of Hilgard[1] are based upon a large number of analyses and wide observation, and appear well adapted to American conditions. These standards give best results when applied to *virgin soils*.

Phosphoric Acid.—Hilgard states that phosphoric acid is seriously deficient in virgin soils when below 0.05 per cent., unless accompanied by a large amount of lime. In heavier virgin soils,

[1] Tenth Census of the U. S.

0.1 per cent. phosphoric acid, when accompanied by a fair amount of lime, secures fair productiveness from eight to fifteen years; with a deficiency of lime, twice the percentage will only serve for a similar time. Soils containing between 0.1 and 0.05 per cent. of phosphoric acid are considered as likely to respond to fertilization with phosphates in a short time. A large supply of organic matter appears, like a large supply of lime, to offset a deficiency in phosphoric acid. Large quantities of hydrated ferric oxides may render even large quantities of phosphoric acid inert and unavailable to plants.

Lime.—Lime is exceedingly important to the soil. Low percentages of potash, phosphoric acid, and potash are adequate when a large proportion of lime carbonate is present. Many of our richest soils are calcareous soils, such as the bluegrass soils of Kentucky, the black prairie soils of Mississippi and Texas, the calcareous prairie soils of Illinois, Indiana, and Iowa. These soils are productive and durable.

Heavy clay soils with less than 0.5 per cent. of lime do not, according to Hilgard's observation, carry the plants characteristic of calcareous soils. The lightest sandy soil should not contain less than 0.10 per cent. of lime; clay loams should contain 0.25 per cent. There is no advantage in more than 2.00 per cent. It appears that an excess of potash may offset deficiency of lime.

The following examples[1] show the effect of lime in overcoming a deficiency in phosphoric acid:

	A	B	C	D
Phosphoric acid per cent.	0.068	0.033	0.030	0.038
Lime	1.254	1.371	0.129	0.034
Potash	0.366	0.699	0.259	0.218

Soils A and B were highly productive, falling off suddenly at the end of 15 or 20 years. Soils C and D scarcely produced 500 pounds seed cotton per acre when fresh, and then only for three or four years. The difference appears to be due to an abundance of lime in the first two, a deficiency in the second two.

[1] Tenth U. S. Census.

	E	F	G
Phosphoric acid per cent.	0.411	0.188	0 042
Lime	0.197	0.047	0.286
Potash	0.422	0.178	0.334

Soil E with a very high percentage of phosphoric acid and only a moderate supply of lime, is very productive. Soils F and G the one with fair lime and low phosphoric acid, the other with the proportions reversed, are both about equally productive.

Potash.—According to Hilgard, sandy soils of great depth may contain less than 0.10 per cent. potash without being deficient therein; sandy loams contain 0.3 to 0.1 per cent.; loams 0.45 to 0.3 per cent., heavy clays and clay loams 0.80 to 0.45 per cent. As a rule, soils containing less than 0.25 per cent. potash are likely to require fertilization with potash salts early, while as much as 0.45 per cent. seems to be sufficient for the same soils. Sometimes, however, a soil rich only in lime and phosphoric acid shows good productiveness despite a low potash percentage, and conversely a high percentage of potash may offset a low percentage of lime.

The availability of the potash depends upon the general character of the soil. With a good supply of available lime and magnesia, the potash of the soil is usually in an available form.

The above standards are for potash estimated according to Hilgard's method. The Association method dissolves less potash and calls for lower standards. Exactly what these standards should be, remains to be determined.

Nitrogen.—Nitrogen is present in the soil in organic compounds which cannot be taken up by plants, and which change slowly into compounds which can be assimilated. This change depends largely upon physical conditions, though the composition and nature of the soil also have an influence. The rapidity of the production of active plant food is more important than the quantity of nitrogen. It is thus evident that it is difficult to fix a standard for nitrogen. It has generally been assumed that 0.10 per cent. is adequate. With less than 0.07 per cent. the soil is

usually deficient. Lime, as with other plant foods, also has an influence.

Examples of Interpretations of Soil Analyses.—The following examples are taken from Hilgard[1]. See accompanying table.

Soils No. 1 and No. 2 are highly productive, and No. 3 is a very good soil. There is a great difference in the chemical composition. No. 1, however, is a heavy clay soil, while Nos. 2 and 3 are sands, and hence need to contain less plant food. Plant roots can also exercise their functions to the depth of three or four feet in them, while in soil No. 1, the roots rarely reach below 12 or 15 inches. Soils No. 4 and 5, almost worthless, are deficient in phosphoric acid, and No. 4 is also deficient in lime. In addition, these soils are underlaid by an almost pure sand at the depth of 12 inches. These facts are sufficient explanation of their character.

PERCENTAGE COMPOSITION OF SOILS.

	No. 1 Stiff buckshot soil, highly productive	No. 2 Very sandy, highly productive	No. 3 Sandy soil, medium productiveness	No. 4 Gray sand, almost worthless	No. 5 Gray sand, almost worthless
Phosphoric acid...	0.30	0.08	0.10	0.02	0.03
Lime	1.35	0.12	0.10	0.02	0.13
Potash	1.10	0.15	0.05	0.06	0.25
	No. 6 Stiff red soil, fairly productive	No. 7 Stiff black prairie, very productive	No. 8 Stiff soil, practically worthless	No. 9 Stiff black prairie, very productive	No. 10 Stiff flatwood inferior quality
Phosphoric acid...	0.19	0.03	0.06	0.10	0.05
Lime.....	0.54	1.37	0.42	1.73	0.18
Potash	0.43	0.70	0.53	0.38	0.75

Soils Nos. 6 to 10 exhibit the effect of lime on the character of the soil; soils 7 and 9 being rich in lime, the others being poor in this ingredient. Soils 7 and 9 are very productive. Soil 7 shows the effect of a large amount of lime in overcoming a deficiency in phosphoric acid, soils 6, 8 and 10, with more phos-

[1] Tenth U. S. Census.

phoric acid, being much poorer soils. Soil 6 is fairly productive in good seasons, soil 8 is considered practically worthless, and soil 10 is of inferior quality.

Iron and Alumina.—The percentage of alumina is an imperfect indication of the amount of clay in the soil. Enough silica seldom dissolves to satisfy the requirement for combining with alumina to form kaolinite. The percentage of alumina extracted is always larger. In numerous cases so little silica is present as to raise a question as to the form of alumina in the soil, the hydrate (Gibbsite) being almost the only possible one, aside from zeolitic minerals.

From 1.5 to 4 per cent. are ordinary percentages of ferric oxide, occurring even in soils but little tinted. Ordinary ferruginous loams vary from 3.5 to 7 per cent.; highly colored red lands have 7 to 12 per cent. ferric oxide and occassionally 20 per cent. or more. Since highly ferruginous soils rarely have a high per cent. of humus, it appears that the iron acts as a carrier of oxygen, and this probably favors oxidation.

Relative Composition of Soils of Arid and Humid Regions.—Hilgard[1] has compiled a great number of analyses of soils of arid and humid regions, made with strong acid, with the result that the soils of the arid region are found to be, on an average, richer in plant food and in lime, than soils of the humid region. Arid soils are prevailingly calcareous, while humid soils are siliceous. This may be in large part due to the fact that the con-

PERCENTAGE COMPOSITION OF SOILS OF ARID AND HUMID REGIONS.

	Humid, average of 696 analyses	Arid, average of 573 analyses
Phosphoric acid	0.12	0.16
Potash	0.21	0.67
Lime	0.13	1.43
Magnesia	0.29	1.27
Sulphur trioxide	0.05	0.06
Alumina	3.66	7.21
Oxide of iron	3.88	5.48
Insoluble and soluble silica	88.21	75.87
Loss on ignition	4.40	5.15

[1] Bulletin No. 3. U. S. Weather Bureau.

tinued leaching of the soils in humid regions washes out the plant food. It may also be partly due to the difference in origin, as many of the humid soils are coastal deposits worn by the water, while many soils in the arid region are comparatively new soils from igneous rocks.

Soils and Subsoils.—If we compare the composition of soils with the corresponding subsoil, we find, almost always, that the subsoil contains less nitrogen than the surface soil. It often contains more potash, more oxide of iron and alumina, and less insoluble material, than the surface soil. This difference is largely due to the percolating water carrying the finer particles of the soil (clay) into the subsoil. There is, however, a good deal of difference in soils in this respect.

Relation of Composition to Type.—Soils of different type differ to some extent in chemical composition, though such is not invariably the case. There is also some variation in individual members of the type. Differences in composition are usually accompanied by differences in properties, productiveness or value of the soil.

AVERAGE PERCENTAGE COMPOSITION OF SOME TYPICAL TEXAS SOILS.[1]

	Phosphoric acid	Nitrogen	Potash	Lime	Magnesia
Norfolk fine sandy loam (5 samples)	0.02	0.06	0.09	0.08	0.03
Norfolk fine sand (5 samples)	0.02	0.02	0.08	0.06	0.06
Susquehanna fine sandy loam (3 samples)	0.02	0.04	0.12	0.11	0.92
Lufkin fine sandy loam (3 samples)	0.04	0.06	0.12	0.14	0.16
Lufkin clay (2 samples)	0.08	0.09	0.62	—	—
Orangeburg fine sandy loam (6 samples)	0.08	0.07	0.63	0.20	0.35
Orangeburg fine sand (3 samples)	0.01	0.07	0.12	0.12	0.09
Wabash clay (3 samples)	0.09	0.13	0.88	—	—
Houston clay (3 samples)	0.04	0.12	0.25	0.51	0.40
Houston black clay (6 samples)	0.04	0.11	0.40	—	—

Detailed analyses and discussion of the soils of the United States are to be found in Bulletin 57 of the Bureau of Soils, and in "Soil Fertility and Permanent Agriculture" by C. G. Hopkins.

[1] Bulletin 126, Texas Station.

CHAPTER X.

ACTIVE PLANT FOOD AND WATER-SOLUBLE CONSTITUENTS OF THE SOIL.

The complete analysis of the soil, or its partial analysis by strong acids, does not show clearly the immediate needs of the soil for plant food. Various weak solvents have been used for this purpose, with some measure of success.

Active plant food is a term used to designate the potash and phosphoric acid soluble in fifth-normal nitric acid. We are not yet able to ascribe different values to the organic nitrogen compounds of the soil.

Dilute Citric Acid.—Numerous attempts have been made to ascertain soil deficiencies by means of weak solvents, such as water, water containing carbon dioxide, weak solutions of citric, hydrochloric, nitric, or oxalic acids, etc.

Dyer[1] found that the root acidity of 100 plants expressed as citric acid, varies from 0.34 per cent. with Solanaceae to 3.4 per cent. with Rosaceae, and averages 0.91 per cent. He based on this work a method of estimating the available plant food by extracting the soil with a 1 per cent. solution of citric acid. The method was applied to Rothamsted soils.[2] The following are some of the results:

BROADBALK WHEAT PLOTS.

Treatment of 50 years	Dissolved by 1 per cent. citric acid				Average yield, 6 years, wheat
	Phosphoric acid	Pounds per acre	Potash	Pounds per acre	
	Per cent.		Per cent.		bushels
3 No manure	0.0078	202	0.0032	83	12¾
7 Phosphoric acid, Potash, Nitrogen	0.0543	1418	0.0232	602	33⅜
2b 4 tons manure	0.0560	1307	0.0384	896	38¾

The amount of phosphoric acid and potash dissolved by 1 per

[1] Jour. Chem. Soc., 1894, 115.

[2] Bulletin 106, Office Exp. Sta., U. S. Dept. Agr.

cent. citric acid thus corresponds with the treatment of the plot and the yield of wheat. The phosphoric acid soluble in strong hydrochloric acid was 0.114 to 0.219 per cent., potash 0.197 to 0.285; thus while there was some difference, it is not a clear indication as to the fertility of the soil.

The application of the citric acid method to soils of varying character has not always given good results. This may be due to several reasons: (1) The plant may have greater difficulty in obtaining citric acid soluble plant food in some soils than in others. In other words, it may be necessary that the standard vary according to the character of the soil, as Hilgard's standards do. (2) The soil may not have been deficient in phosphoric acid or potash when it was supposed to be. (3) Different rates of change of potash and phosphoric acid into more soluble compounds in different soils may interfere.

According to Dyer, less than 0.01 per cent. phosphoric acid or potash soluble in phosphoric acid indicates a deficiency.

Other Weak Solvents.[1]—These include N/5 nitric or hydrochloric acid, N/200 hydrochloric acid,[2] and N/5 oxalic acid which have been suggested for the same purpose as 1 per cent. citric acid. Some of these solvents have the advantage of greater ease of manipulation than citric acid. The results vary according to the solvent employed.

The most promising solvent is fifth-normal nitric acid. Fifth-normal nitric or hydrochloric acid gave the same results on certain of the Rothamsted soils as citric acid, and upon some other soils tested by the Association of Official Agricultural Chemists the results were more nearly in accordance with the needs of the plant.

Factors of Availability of Plant Food.[3]—The amount of any given plant food which is withdrawn from the soil by the plant does not depend upon one condition only, but is dependent upon

[1] See Proceedings Association Official Agr. Chem., Bulletins 47, 49, 51, 56, 67, 73, Division Chem., U. S. Dept. Agr.

[2] Moore, Jour. Am. Chem. Soc., 1912, p. 791.

[3] Fraps, Am. Chem. Jour., 1904, p. 1.

a number of factors. These factors may be grouped as follows:

(1) The quantity of the element present at the beginning of the growing season in forms of combination which can be partly or completely absorbed by the plant. This may be called *chemically available* plant food.

(2) The condition of the soil particles. Compounds chemically available may be enclosed in the soil particles so as not to be exposed to the action of plant roots. Such compounds are *physically unavailable*. If the encrusting substance is removed, such bodies become chemically available.

(3) The amount of the plant food transformed during the growing season into forms of combination which can be absorbed by plants. This factor is certainly of importance with respect to nitrogen; its importance in the case of phosphoric acid and potash is apparently not so great but the matter requires study. This factor may be called *weathering availability*.

(4) The nature of the plant. Plants differ in both their capacity for absorbing food and their need of it. Whatever the cause of these differences, there is no doubt but that they exist. We will call this factor *physiological availability*.

The character of the soil, its chemical composition, the conditions which prevail during the growth of the plant, and perhaps other factors influence the amount of plant food taken up.

Factors Influencing the Composition of the Soil Extract.[1]—The amount of phosphoric acid extracted from the soil by a given solvent is the difference between that dissolved from the phosphatic or potash mineral and that absorbed by the fixing particles of the soil. That is to say, the soil extract does not necessarily represent the solubility of the mineral exposed to the action of the solvent, but is the resultant of the solvent and fixative forces. Furthermore, the quantity of phosphoric acid exposed to the action of the solvent depends upon its condition in the soil and the solubility of protecting material in the solvent used. If the phosphate mineral is enclosed within quartz,

[1] Texas Bulletins 126-145.

it is quite effectually protected from any solvent. If it is contained within zeolites, it may be affected by some solvents and not by others. If it is contained in carbonate of lime, the latter will be dissolved by any acid solvents, with consequent exposure of the included phosphate to the action of the solvent.

The quantity of phosphoric acid or potash contained in the soil extract thus depends upon three factors:

(1) The quantity of phosphate or potash mineral exposed to the solvent, and its solubility under the conditions of the extraction.

(2) The solubility of the soil materials which protect or enclose phosphates or potash compounds.

(3) The power of the soil to fix phosphoric acid or potash under the conditions of the extraction.

The strength of the solvent, its nature, the period of digestion, the temperature, and the proportion of soil to solvent, all affect the quantity of phosphoric acid and potash contained in the soil extract, but they have their effect through action on the three factors mentioned above.

Solubility of the Soil Minerals.—This subject[1] is studied by bringing phosphate or potash minerals in contact with N/5 nitric acid, in the proportions in which these minerals may occur in the soil, and under the conditions of the soil extraction.

Phosphoric Acid.—The phosphates of lime are completely soluble, the precipitated phosphates of iron and aluminium are completely soluble, and vivianite and triplite are nearly so, in N/5 nitric acid. The aluminium phosphates (variscite and wavellite) and the basic ferric phosphates are comparatively slightly dissolved.

It is hardly probable that ferrous phosphate (vivianite) is of common occurrence in ordinary cultivated soils, though it may exist in some soils which are not well aerated. Fifth-normal nitric acid dissolves calcium phosphates completely, but dissolves mineral aluminium phosphates or basic ferric phosphates only to a slight extent. It thus distinguishes between these two classes

[1] Texas Station Bulletins 126-145.

of compounds in the soil. Apatite, phosphate rock, ferric phosphate (precipitated), aluminium phosphate, vivianite, and triplite are practically equally soluble. We also feel justified in saying that acid phosphate would be completely dissolved. But no one can yet claim that these materials possess the same value to plants. Fifth-normal nitric acid may not distinguish between minerals which have unequal values to plants. We have no solvent which would dissolve phosphoric acid from the phosphates mentioned, in the same proportions as would be taken from them by plants. What we cannot do with known mineral phosphates of known character outside of the soil, we could not expect to do with the same phosphates after they are put into the soil, and with the unknown phosphates already within the soil.

Soils may, therefore, contain equal quantities of phosphoric acid soluble in fifth-normal nitric acid, and yet give up unequal quantities of phosphoric acid to plants on account of differences in the phosphates present. This consideration must give rise to caution in comparing the results of all kinds of soils with one another.

Only those soils should be compared which probably contain the same kinds of phosphates. Soils widely dissimilar in origin and character should not be compared, unless there is evidence that they contain similar phosphates.

Study of potash dissolved from minerals in a similar way shows that very little is taken from the felspars, microcline and orthoclase, less than ten per cent. from glauconite and biotite, and from 16 to 60 per cent. from muscovite, nephelite, leucite, phillipsite, and apophyllite. Potash absorbed by chabazite and some other minerals is extracted to the extent of 70 per cent. The dissolved potash thus represents a large portion of some easily dissolved mineral, or a small portion of some difficultly attacked mineral.

Fixation of the Dissolved Phosphoric Acid and Potash.—The soil has the power to withdraw potash and phosphoric acid from solution, both in water and in acids. The method of studying this factor consists in extracting two portions of the soil of

known fixing power with the solvent, one part with the acid alone, and the other with a known quantity of phosphoric acid or potash. The quantities should be such as might be dissolved from the soil. The following is an example:[1]

	Phosphoric acid Parts per million
Extracted from soil alone	8.5
Added to solvent	194.0
Total present	202.5
Actually recovered	48.0
Absorbed by soil	154.5

With 17 soils, the fixation of the added phosphoric acid ranged from 5 to 94 per cent. of the quantity added. Thus the phosphoric acid extracted by the N/5 nitric acid does not necessarily represent that which has gone into solution, but represents the resultant of the solvent, and the fixing power of the soil. With some soils, the fixing power is so high that it must be considered very seriously in interpreting the results of the analysis. Fixation also takes place from acids stronger than fifth-normal.

Fixation of potash takes place under the same conditions as the fixation of phosphoric acid, but to a much less extent, and the factor of fixation is much less important with potash.

Soils containing easily-soluble phosphoric acid or potash compounds give decreasing amounts to successive extractions, but soils containing little or no compounds of high solubility give successive extracts of nearly constant composition.

Solubility of Constituents of the Soil.—The solubility of the constituents of the soil must be considered as a factor in the analysis of soils with weak solvents. If any quantity of the soil passes into solution, phosphates will thereby be exposed to the action of the solvent, which were protected from the action of soil moisture and roots, and which are really *physically unavailable*. This factor must be given careful consideration. For example, N/5 nitric acid dissolves 320 parts per million of lime (CaO) from one soil, while from another soil it dissolves 53,250 parts, which corresponds to nearly 10 per cent. carbonate of

[1] Texas Station Bulletin 126, p. 16.

lime. The amount of phosphoric acid and potash brought into action through the solution of the lime in the soil first named, may not be large, but in the case of the second soil, 10 per cent. of the soil enters into solution, and all the phosphoric acid and potash protected within this 10 per cent. is exposed to the action of the solvent. This action is further emphasized, in the case of the soil just mentioned, by the fact that a second treatment with acid dissolves 43,400 parts per million of lime, and a third treatment dissolves 46,360 parts, making a total of about 14 per cent. of lime dissolved from the soil, corresponding to about 25 per cent. carbonate of lime.

This soil, of course, represents an extreme instance, but it emphasizes the difference between a calcareous and a non-calcareous soil. In a non-calcareous soil, the phosphoric acid and potash inclosed within the soil particles are protected from the solvent, while in a calcareous soil, that portion of the phosphates and potash minerals included in the calcareous matter dissolved by the acid is exposed, and may be dissolved.

Since the plant food dissolved from a non-calcareous soil is present on the external surface of the soil grains, and accessible to the roots of the plants and the action of soil moisture, while that dissolved from calcareous soils is, without doubt, in part included within the soil grains, and not accessible to plant roots, it is obvious that calcareous soils may contain a larger quantity of seemingly active plant food than non-calcareous soils, and yet require fertilization on account of the phosphoric acid being protected.

Two calcareous soils may also contain the same amount of active plant food, and yet differ in the amount plants can take from them. In one the plant food may be on the extreme surface of the soil grains, in the other it may be disseminated through them.

Calcareous soils are more durable than non-calcareous soils. This may be explained by the fact that the gradual weathering of such soils continually exposes fresh surfaces of plant food.

Significance of the Dissolved Plant Food.[1]—In considering the significance of the dissolved plant food, it is necessary to regard the active phosphoric acid and potash, the "acid consumed," and the fixing power of the soil. The fixing power is of importance chiefly in connection with soils which fix more than 80 per cent. phosphoric acid. With such soils, the extracted phosphoric acid may, or may not, represent the soluble phosphates.

The "acid consumed" is a measure of the bases dissolved by the solvent, and is estimated by titrating 10 cc. of the solution after the extraction is complete.

When 10 parts per million of phosphoric acid, or less, is extracted, associated with a fixing power of less than 50 per cent., and with acid consumed less than 90 per cent., it indicates that practically none of the phosphoric acid of the soil is present as apatite, calcium phosphate, or similar compounds, but must be present as basic iron or aluminium phosphates or in organic combination. When 10 parts phosphoric acid, or less, are present and the soil has a high fixing power for phosphoric acid (75 per cent. or more), calcium phosphates may or may not be present. That is to say, the method can not in this case distinguish between phosphoric acid which goes into solution from calcium phosphate and is then removed by fixation, and that which comes from the basic phosphates of the soil. The origin of the soil will throw some light upon the matter. If the soil is geologically old, the phosphoric acid has probably all been converted into basic phosphates. If the soil has been recently formed from rocks containing apatite and other phosphatic minerals, it is possible that calcium phosphate may still be present and the same is true if the soil has been fertilized. In the majority of soils having a high fixing power and a low content of phosphoric acid, provided that they have not been fertilized, the phosphoric acid is probably present as basic iron and aluminium phosphates.

A soil of high fixing power such as above mentioned would yield up the same quantity of phosphoric acid to the solvent, whether fertilized or not fertilized, unless a very heavy applica-

[1] Texas Station Bulletins 126 and 145.

tion of phosphoric acid has been made. One thousand pounds of 16 per cent. acid phosphate would represent an application of 80 parts per million of phosphoric acid, and this heavy application would not increase very much the phosphoric acid removed from soils of very high fixing power.

A soil containing 100 parts per million of phosphoric acid, with a low acid consumed, and with a fixing power of less than 50, probably contains a corresponding amount of calcium phosphate accessible to the roots of plants.

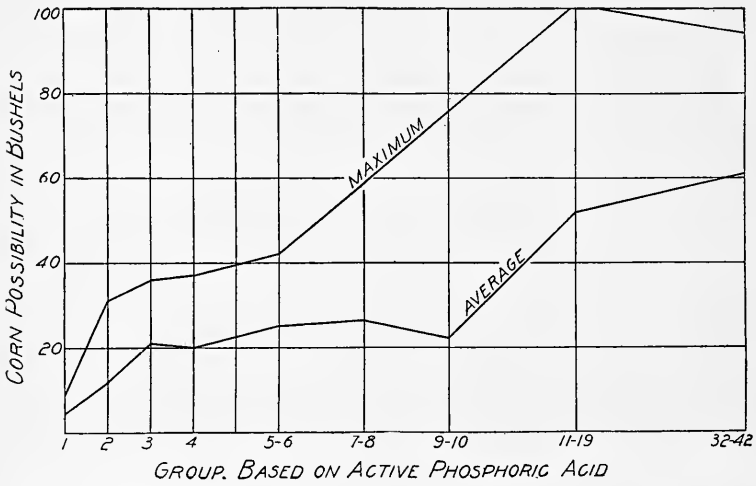


Fig. 39—Relation of the active phosphoric acid of the soil to the phosphoric acid withdrawn by crops in pot experiments, expressed as bushels corn per acre.

A soil containing 100 parts per million of phosphoric acid, with an acid consumed of 20 per cent., may or may not expose much phosphoric acid to the roots of plants. It is impossible to say how much of it is protected by the calcareous material.

It is impossible to distinguish phosphoric acid in its several different forms. For example, suppose plots were fertilized with equal quantities of phosphoric acid, Thomas phosphate, phosphate rock, acid phosphate, and apatite. We could not expect to find a relation between the phosphoric

acid dissolved from these plots and the crop production. All these materials would give up their phosphoric acid equally well to the solvent used.

A soil containing less than 50 parts per million of active potash probably contains all its potash in the form of highly insoluble silicates, such as the felspars. A soil containing over 50 parts per million of active potash contains some of more easily dissolved potash minerals or compounds. Since the solvent does not

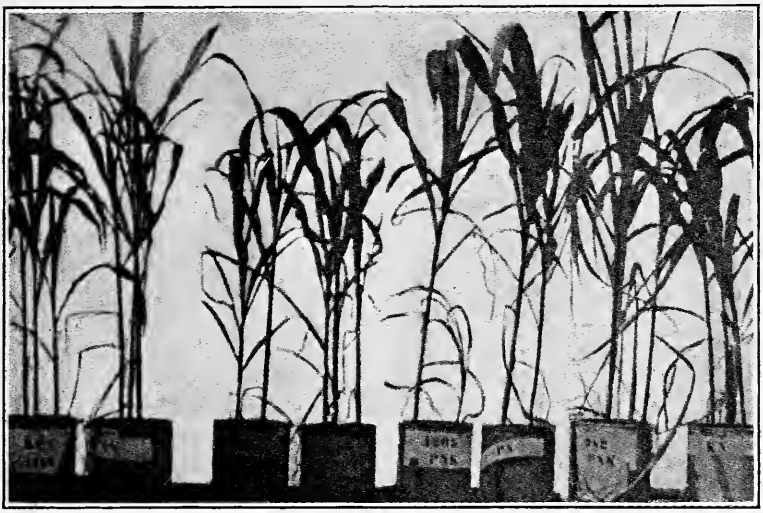


Fig. 40.—Corn grown with and without phosphoric acid on four soils containing 60 to 100 parts per million of active phosphoric acid, Texas Station.

decompose such minerals fully, and some fixation also occurs, the quantity of potash extracted is less than the quantity present in easily soluble compounds.

Relation of Active Phosphoric Acid to Growth in Pot Experiments.—At the Texas Experiment Station, studies were made of the relation between the active phosphoric acid present in the soil and the crop produced in pot experiments. The comparison was made between the crops grown with phosphoric acid, nitrogen, and potash, and those grown with nitrogen and potash only. The

behavior of the corn crop was closely related to the quantity of active phosphoric acid in the soil. Soils containing 20 parts per million, or less, of active phosphoric acid are clearly deficient in phosphoric acid. Soils containing 30 to 100 parts per million

Fig. 41.—Corn grown with and without phosphoric acid on four soils containing less than ten parts per million of active phosphoric acid, Texas Sta.

were, as a rule, deficient. Soils containing 100 to 200 parts per million were deficient in about one-half of the experiments.

Average Corn Possibility and Availability of Phosphoric Acid.

Active phosphoric acid (parts per million)	Corn equivalent (bushels per acre)	
	Average	Maximum
0 to 10	4.5	9.0
10 to 20	12.5	31.0
20 to 30	20.8	36 0
30 to 40	19.7	37.0
40 to 60	21.4	42.0
60 to 80	26.5	59.0
80 to 100	22.0	39.0
100 to 190	52.5	101.0
210 to 420	60.7	91.0

The quantity of phosphoric acid withdrawn from the soil was also related to the quantity of active phosphoric acid. In the

table[1] on page 190 the quantity of phosphoric acid withdrawn by the crop is expressed as bushels of corn per acre which could be produced with it.

Potash.[2]—A similar series of experiments carried out with potash lead to similar results. The percentage of deficient crops decreases with the quantity of active potash in the soil. The average percentage of potash in the crop increases with the percentage of active potash in the soil. The actual quantity of potash

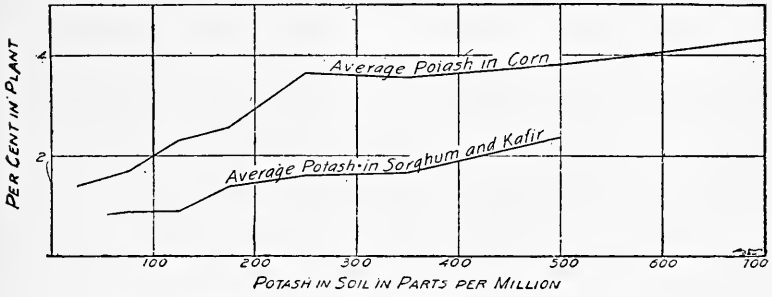


Fig. 42.—Relation of the potash content of the crop to the active potash of the soil.

removed by the crop increases with the active potash of the soil. After cropping, the soil, on analysis, was found to contain less active potash than it did before cropping, showing the disappearance of active potash due to the crop.

Relation of Active Potash to Pot Experiments.

Active potash in soil (parts per million)	Percentage of crops		Average weight of crops without potash divided by crop with potash	Average percentage of potash in corn crop
	Deficient in potash	Injured by potash		
0 to 50	86.7	6.7	67	1.38
50 to 100	55.1	16.7	79	1.70
100 to 150	54.3	16.1	84	2.29
150 to 200	39.1	17.2	91	2.55
200 to 300	37.5	31.3	100	3.65
300 to 400	42.6	25.5	98	3.53
400 to 600	15.0	45.6	101	3.83
600 to 800	18.0	43.8	116	4.31

[1] Texas Station Bulletin 126, p. 69.

[2] Texas Station Bulletin 145.

The actual amount of potash removed, on an average, from the different soils, is given in the following table. In order to make the table more concrete, the amount of potash is also expressed in bushels of corn per acre which could be produced by this quantity, both stalk and grain included:

Active potash in soil (parts per million)	Active potash removed (parts per million)		Corn in bushels equivalent to average potash removed
	Average	Maximum	
0 to 50	29.7	53.4	58.6
50 to 100	37.2	143.2	74.4
100 to 150	51.0	176.2	102.0
150 to 200	80.9	249.6	161.8
200 to 300	120.0	434.6	240.2
300 to 400	150.9	354.8	313.8
400 to 600	119.4	295.8	238.8
600 to 800	206.9	380.8	413.8

Importance of the Active Plant Food.—The active plant food is thus related, on an average, to the ability of the soil to supply plant food. Variations undoubtedly occur, due to variations in the nature of the active plant food. The relation of the active plant food to field results must be studied and worked out. Deficiency as shown in pot experiments must be considered as relative deficiency, and in applying the results to field conditions, the possibilities of the soil under the prevailing climatic conditions must be considered. For example, in our pot experiments, soils containing 100 to 150 parts per million of active potash were deficient in potash in 54.3 per cent. of the tests, and yet on an average, they gave up enough potash for 102 bushels of corn, the maximum being 352 bushels. In other words, the pot experiments demanded more potash than would suffice for the crop indicated above. Had the demands for potash been smaller, the soil would not have been deficient.

The importance of the estimation of the active potash and phosphoric acid is to show the relative deficiency of the soil for these elements. The tables we have given are an aid in this consideration. For example, a soil containing 10 parts per million of active phosphoric acid and 50 parts of active potash, would

have an average corn possibility of 4.5 bushels for phosphoric acid and 58.6 bushels for potash. Evidently there is greater need of phosphoric acid than of potash, and the two become equal by the addition of sufficient phosphoric acid for 54.1 bushels corn.

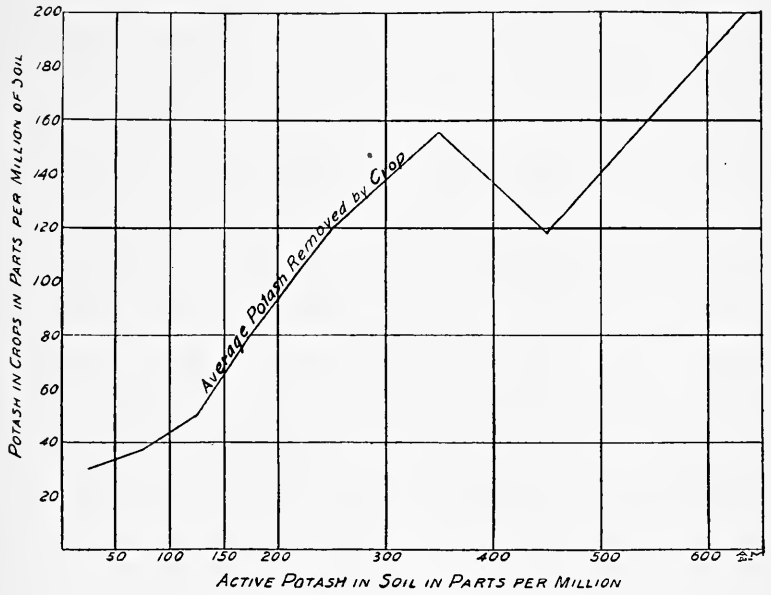


Fig. 43.—Relation of the potash removed by crops in pot experiments to the active potash contained in the soil.

This, however, is only an illustration. Field experiments must show the exact relation of the two.

Relation of Total Nitrogen to Results of Pot Experiments.[1]—Pot experiments similar to these just described have been used to trace the relation between the total nitrogen of the soil and the effect of the fertilizers. They will be described here on account of their relation to the preceding work. The effect of the fertilizer is, in general, related to the content of nitrogen in the soil. The percentage of nitrogen in the crop increases as the percentage of total nitrogen of the soil increases. The average corn possibility,

[1] Texas Station Bulletin No. 151.

in bushels per acre, based on the quantity of nitrogen removed

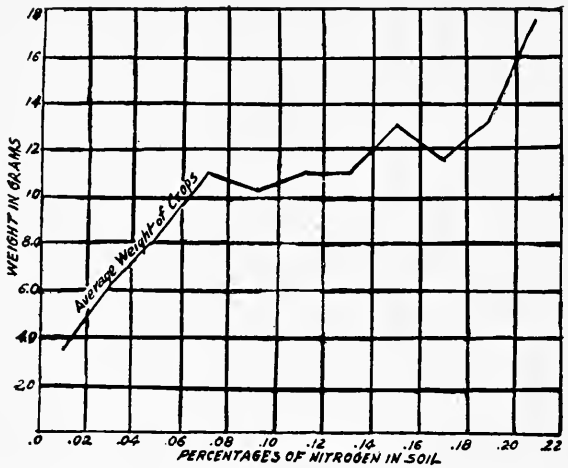


Fig. 44.—Relation of total nitrogen to the average weight of the crops grown without addition of nitrogen in pot experiments.

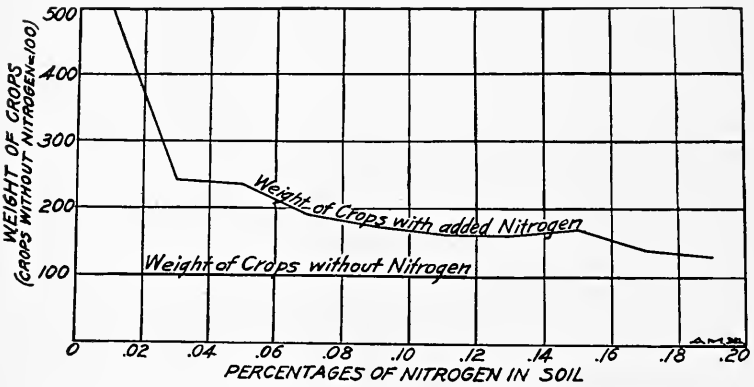


Fig. 45.—Relation of total nitrogen of the soil to the average effect of fertilizer nitrogen in pot experiments.

from the soils in pot experiments, is given in the following table:

Percentage of nitrogen in soil	Average corn possibility (bushels per acre)
0.000 to 0.02	5.7
0.021 to 0.04	9.4
0.041 to 0.06	13.6
0.061 to 0.16	22.3
0.161 to 0.18	42.9

Interpretation of Soil Analysis with Weak Solvents.—The "corn possibility" figures may be used for the purpose of ascertaining the probable relative deficiency of a soil. Suppose, for example, a soil contains .086 per cent. nitrogen, 8 parts per million active phosphoric acid, and 105 parts per million active potash. Referring to the tables, we find:

	Corn possibility (bushels)
For nitrogen	22.0
For active phosphoric acid	4.5
For active potash	102.0

Thus this soil would probably be most deficient in phosphoric acid, next in nitrogen, and least in potash, if tested in pot experiments.

The active phosphoric acid and potash and the total nitrogen are not, however, the only things to consider under field conditions. The form of the phosphoric acid, depth of soil, kind of cultivation, season, etc., all influence the size of the crop. It is thus not possible to say that the corn possibility represents what should actually be produced in the field. Field results must be worked out for different localities, as no doubt climate and temperature will cause soils of the same analysis to give different results in different sections.

The fact that there is possibly a close relation between chemical analyses and field results is shown in certain results secured at the Texas Experiment Station.[1] Eight soils in which total nitrogen was probably the controlling condition, averaged 11 bushels per acre corn possibility, while the actual yield as claimed by the farmers was 18 bushels. Five soils controlled by active

[1] Proc. Int. Cong. of Applied Chem., 1912.

phosphoric acid averaged 12 bushels corn possibility, and actual production averaged 14. Considering the fact that the actual yields given were estimates, and that the corn possibility is probably a little low, the agreement is good. This matter requires considerably further study.

Water-Soluble Constituents.—The water-soluble constituents of the soil are of significance from the fact that material can enter the plant only in solution. The root is composed of cells, through which there are no openings for the entrance of solids.

When a liquid containing a substance in solution is

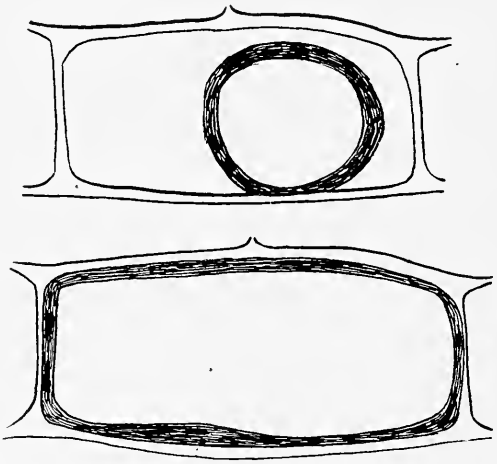


Fig. 46.—Enlarged plant cell, normal below, and with the protoplasm contracted by nitrate of soda above.

brought in contact with another portion of the same liquid which does not contain that substance, the dissolved substance passes into that portion until all parts of the liquid have a uniform composition. This is called diffusion. The same occurs when the liquid is separated by a membrane, which the dissolved substance is able to penetrate. Substances which cannot generally pass through membranes are termed colloids, examples being albumen, glue, etc. Salt, sugar, calcium sulphate, which can pass through, are called crystalloids. If, then, a plant cell is brought

in contact with a solution of a substance which can penetrate the membrane, diffusion will take place until the number of ions of the same kind entering the cell walls is equal to the number leaving it. If the cell life appropriates any of the ions, and holds them, so that they become incapable of diffusion, the ions continue to enter the cell until the cell life becomes satisfied, and the number entering and leaving become equal. The same phenomenon occurs with an aggregate of cells or the entire plant. It is then possible for plants to extract elements from very dilute solutions, and accumulate them in their tissues, and also for plants to live in comparatively strong solutions of a salt without taking up large quantities of the substance.

Diffusion into Cells.—According to Pfeffer, plant cells are composed of three parts; an outer cell wall, of cellulose or some other membrane; a layer of protoplasm or living material adherent to the cell wall; and the cell sap. The cell wall is in general more permeable to dissolved substances than the protoplasm, and hence many substances pass through the cell walls but not through the living plasma within. "It is indeed possible that the water and salts absorbed by the roots pass mainly if not entirely through the walls of living cells or the walls and cavities of dead wood fibers, so that only on reaching the leaves of a tree do they penetrate the living protoplasts there." The character of the cell wall and of the protoplasm membranes determine whether a given substance will penetrate to the interior of a cell, and any such substance will continue to be absorbed until a condition of equilibrium is reached, when all further absorption ceases. If this condition of equilibrium is disturbed, absorption may continue, and relatively large quantities of a particular substance may be absorbed from a very dilute solution.

Every substance which can pass through the different cellular membranes penetrates the protoplasm independently of whether it is useful, unnecessary, or even injurious.

Cells may convert bodies which diffuse into them into non-diffusing compounds, and the substance will continue to enter as long as this takes place. The non-diffusing compound may be

soluble or insoluble. Thus methyl blue is fixed in an insoluble form in the roots of *Azalla,* while in the roots of *Lemna minor* it accumulates in a dissolved form. In both cases the dye is accumulated from very dilute solution, and the cells become distinctly colored. The dissolved substances in the cell sap (sugar, salts of organic acids, potassium nitrate, etc.,) must be present in a non-diffusing form. The presence of nitrates in dead cells does not indicate that they are so present in the living cell, for the non-diffusing substances may decompose immediately on the death of the cell.

Transpiration Movements.—Diffusion alone is a very slow movement. It requires 319 days to transport 1 mg. the distance of 1 mm. from a 10 per cent. solution into pure water. Most of the material which enters the roots of a plant, though it must diffuse through the root wall, enters in the current of water afterwards transpired, rather than by diffusion alone.

Active transpiration must lead to the continuous introduction of new traces of salts by the water current, since backward diffusion is slow. This explains how relatively large amounts of saline materials are sometimes found in plants. Nobbe and Siegert actually found patches of saline incrustation on the leaves of buckwheat and barley when the plants were grown in a one per cent. solution of salts. Soluble incrustations are sometimes found on plants, and calcareous scales are often found on the leaves of many Saxifrage and other plants. Transpiration may also aid in the deposition of silica in the cells of plants.

Absorption by the Root.—Excepting carbon dioxide (and nitrogen in some cases perhaps) the roots absorb all the compounds used to buld up the plant; namely, water, hydrogen, and oxygen, and all the other elements in the form of salts. Salts of iron, calcium, magnesium, sodium, manganese, potassium, silicon, chlorine, nitrogen, sulphur, and phosphorus are thus taken up.

Salts in solution are more or less decomposed into ions, which are atoms or groups of atoms charged with electricity. Thus, sodium chloride is broken down into the ions, Na and Cl, sodium sulphate into Na and SO_4, potassium nitrate into K and NO_3.

Plants have the capacity of taking up one or the other of these ions alone. From a solution of potassium chloride, the plant may take up more potassium ions than chlorine ions, leaving hydrogen in place of the potassium. The liquid would then become acid from the presence of hydrochloric acid. The plant may remove the nitrate ions from a solution of calcium nitrate. The calcium ion would then unite with carbon dioxide and form insoluble calcium carbonate.

The above considerations are essentially modified in the presence of two or more salts; as a rule, when two salts are present, which are required by the plant, their absorption is accelerated. For example, potassium salts are taken up in much larger quantity when a calcium salt is present. Potassium nitrate may be entirely removed from a solution containing calcium nitrate. In the presence of other ions, the potassium ion, nitrate ion, phosphate ion, and sulphate ion can be completely removed from solution, while calcium or magnesium ions become more concentrated in the solution, as a rule.

A study of the effect of the amount of water evaporated upon the ash constituents taken up has shown that the stronger the evaporation, the more dilute is the solution taken up by the plant, but at the same time the more substance is taken up, since the decrease in concentration is in a less ratio than the increase in water evaporated.

Soil Solution.—The soil solutions are exceedingly dilute. From what has been said, however, it is seen that plants may withdraw nourishment from very dilute solutions. It is self-evident, that when the dilution goes below certain limits, diffusion will not take place with sufficient rapidity to satisfy the requirements of the plants, and limits are conceivable at which only a minimum growth will take place.

In other words, there is an optimum of concentration, above and below which a lesser production of plant substance takes place. Below, because transpiration and diffusion do not provide sufficient food.

An example of the effect of dilution is presented below.

	Yields gm. dry matter
1 part per thousand	0.4934
3 parts per thousand	0.7320
5 parts per thousand	1.1540

The plants were grown in water containing a mixture of the various necessary salts.

Solvent Action of Roots.—Although plants can take up substances only in a state of solution, they have some power of bringing substances into solution. Etchings showing the shape of the root can be obtained by causing plants to grow upon polished marble, and such etchings are often found in nature.

The solvent action of roots is aided by the intimate contact between root hairs, and soil particles, the latter often being literally imbedded in the roots. The solvent action observed may be brought about by the action of carbonic acid given off by the roots, and the etchings mentioned above may be formed in this

Fig. 47.—A root hair, highly enlarged, showing the intimate contact of root and soil.

manner. According to Czapek, roots excrete potassium acid phosphate, which has an acid reaction. The vegetable acids in the root juices may also be effective, without actually passing through the membrane. The vegetable acids are dissociated to a certain extent into hydrogen and other ions; for example, oxalic acid may dissociate into the ions H and HC_2O_4. The ion HC_2O_4 may be held in a non-diffusing condition, while the hydrogen is at liberty to pass through the membrane, and thus exert an action upon external substances. In this way there may be an exchange of H and Ca ions, for example. Whatever the cause of the solvent action of plant roots, it is well demonstrated that plants can take up material not dissolved in the solution which extends between the soil particles.

Water Extract of Soils.—In arid climates, water-soluble material may accumulate and give rise to alkali. The solvent action of water in a soil under natural conditions is increased by the carbon dioxide formed from decaying organic material.

On shaking a soil with water, a small amount of soil ingredients enters into solution. The extract does not represent the solubility of the soil constituents in water, but is the resultant of the solvent and fixative forces, as in the case of the acid extract. The soil has a much greater power of withdrawing material from water than from acid solution, and hence the aqueous extract is a much poorer measure of the solubility of soil materials. For example,[1] on shaking a certain soil with water, the resulting extract contained 2.3 parts per million of phosphoric acid, and the same results were secured on shaking it with a solution of potassium phosphate containing 10 parts per million of phosphoric acid.

Composition of the Water Extract.—The soil extract varies widely in composition, even from soils of the same type. The following results are compiled (and recalculated) from Bulletin 22 of the Bureau of Soils:

VARIATIONS IN COMPOSITION OF SOIL EXTRACT.

	Parts per million of soil			Pounds per acre-foot		
	Phosphoric acid	Nitrogen	Potash	Phosphoric acid	Nitrogen	Potash
	P_2O_5	N	K_2O	P_2O_5	N	K_2O
Windsor sand	1.6- 7.6	0.2- 7.2	13.1- 55.3	5.6-26.6	0.7-25.2	45.8-193.6
Norfolk sand	1.0- 9.7	0.2- 6.4	13.9- 54.0	3.5-53.9	0.7-22.4	48.7-189.0
Sassafras loam	1.3-12.7	0.1-10.4	9.5- 56.2	4.5-44.5	0.3-36.4	33.3-196.7
Leonardtown loam	1.7- 9.7	trace 16.5	72.1- 62.0	5.9-33.9	trace 57.8	42.3-217.0
Cecil sandy loam	0.3-16.3	trace 7.7	9.0- 87.2	1.0-57.1	trace 26.9	31.5-285.2
Cecil clay	1.4-24.0	trace 9.2	5.9-100.6	14.9-88.0	trace 32-2	20.7-352.1

The Bureau of Soils claims that the composition of the soil extract is practically constant in all soils, but it is difficult to see how the preceding analyses can be reconciled with such claim.

[1] Texas Station Bulletin 82, p. 16.

If we assume that in the production of one gram of dry matter 500 grams water are transpired, we can calculate the concentration of the absorbed water required to give the average composition of various plants. This has been done and the results are in the following table:

	Percentage in dry matter of plant		Necessary concentration of soil solution per million	
	Phosphoric acid	Potash	Phosphoric acid	Potash
Meadow hay	0.59	1.86	10	37
Timothy grass	0.80	2.36	16	47
Winter wheat (bloom)	0.53	1.94	11	39
Oats, in bloom	0.68	2.62	14	52
Barley, in bloom	0.67	1.65	13	33
Sugar cane	0.16	0.45	3	9
Red clover	0.66	2.22	13	44
Alfalfa	0.63	1.73	13	15

If we compare this table with the preceding, we find that the soil moisture does not contain enough phosphoric acid. In only three of the soil series is even the maximum content of phosphoric acid sufficient for the requirements of any of the plants (except sugar cane). The minimum content of the soil moisture in potash falls below the concentration required, but the maximum of all series of soils is above the maximum requirements of the plants given above.

Investigations were made by King[1] upon the water-soluble salts of the soil, and the yield of corn and potatoes on eight types of soil in North Carolina, Maryland, Pennsylvania, and Wisconsin. He concludes that "there is a well-marked tendency for larger amounts of water-soluble salts to be removed by the methods adopted from the soils upon which the crops have made the largest yields." The water-soluble material was estimated to the depth of four feet. The addition of fertilizers was also found to increase the water-soluble salts, and where determined under large and under small plants in the same field, differences were also

[1] Bulletin 26, Bureau of Soils.

evident, as the soil under the larger plants contained more water-soluble materials.

The following table shows the water-soluble material dissolved from several types, according to King's[1] investigations:

SALTS DISSOLVED BY WATER FROM SURFACE FOUR FEET OF SOIL TYPES (POUNDS PER ACRE).

	K	Ca	Mg	NO_3	HPO_4
Norfolk sandy soil	210	404	197	162	141
Selma silt loam	154	415	163	97	120
Norfolk sand	190	387	173	147	191
Sassafras sandy loam	175	375	177	128	135
Hagerstown clay loam	192	1,036	306	262	221
Hagerstown loam	246	910	281	429	196
Jonesville loam	364	1,070	420	560	336
Miami loam	257	1,049	386	200	288
Average	224	705	263	106	66

The average quantity of plant food dissolved from the soil was sufficient to produce the following amounts of clover hay:[2]

	Tons
Potash	7.2
Lime	24.6
Nitrogen	2.7
Phosphoric acid	13.2

[1] Bulletin 26, p. 65, Bureau of Soils.

[2] Bulletin 20, p. 78, Bureau of Soils.

CHAPTER XI.

CHEMICAL CHANGES.

The soil is not inert, but a great number of changes take place in it. some purely chemical, and others brought about by the action of bacteria and other forms of life. The most important changes have to do with organic matter and nitrogen. The bulk of the nitrogen in organic forms in soils is useless to plants, and must be changed before it can be taken up by them. Phosphoric acid and potash are fixed by the soil, and their compounds undergo various changes.

Changes of Nitrogen in the Soil.—Many changes take place in the nitrogen of the soil, all brought about by bacteria. There is, first, the transformation of organic nitrogen into ammonia, termed *ammonification*. Next is the change of organic matter, ammonia, and nitrites, to nitrates, a change called *nitrification*. Another change is the destruction of nitrates, either nitrites, ammonia, protein, or free nitrogen being formed, a change called *dentrification*. A further change is the production of organic compounds from the elementary nitrogen of the air, a change caled *nitrogen fixation*. As these changes are brought about by the agency of bacteria, it is necessary to give a little space to the study of soil bacteria.

Soil Bacteria.[1]—Bacteria are organisms so small as to be seen only under the highest power of the microscope. They are grown either in liquids or on the surface of slices of potatoes, solidified plates of gelatin, agar, or similar material, the proper nourishment being supplied. The plate method is used for isolating and studying bacteria, since many kinds of bacteria form characteristic colonies, and a pure culture can easily be secured therefrom. Unfortunately many important soil bacteria do not grow well on such plates. This is especially true of the nitrate bacteria. Since bacteria abound everywhere, it is necessary in the study of bacteria to destroy all those which are originally

[1] Review of Investigations of Soil Bacteriology, Voorhees and Lipman, Bulletin 94, Office of Exp. Sta.

present in the vessels or materials which are to contain those to be studied, and to guard as much as possible against contamination from outside sources, such as the air. Bacteria may be pres-

Fig. 48.—Colonies of bacteria growing in a gelatine plate. Kansas Station.

ent as spores which are a resting, or "seed" stage of bacteria, and are much more difficult to destroy than the growing bacteria.

Methods.—Forceps, cover slides, etc., are sterilized by heating in a bunsen burner. Glassware, such as flasks, beakers, pipettes, etc., and other articles which can be subjected to it, may be sterilized by dry heat one hour in an air bath or oven at a temperature of 170° C. In order to prevent contamination after sterilization, they are placed in closed vessels until needed. Flasks and pipettes may be plugged with cotton wool, which allows the entrance of air, but excludes bacteria.

Distilled or tap water is sterilized by boiling. Boiling for five minutes will kill ordinary germs if no spores are present. Media are often sterilized by heating in steam at 100° C. Steaming one and one-half hours will sterilize any medium, but this injures some media, especially gelatin. The method adopted in such cases is to steam for 15 minutes on three successive days. This rests on the principle that all bacteria in the non-spored condition are killed the first day, while the spores which are not killed, develop into bacteria and are killed the second or third day. A rapid and effective method of sterilization consists of steaming under pressure at 115° C. from 7 to 15 minutes.

A variety of media are used for growing bacteria, such as meat extract, broth, blood serum, milk, slices of potatoes, etc.

Number of Bacteria.—One method of estimating the number of bacteria in the soil is as follows: About a gram of the soil is shaken from a weighed tube into a liter of sterilized water, and the tube reweighed. The soil and water are then mixed thoroughly. Tubes of modified agar[1] are then melted, and one inoculated with 0.1 cc. of water, another with 1.0 cc. The agar is then poured into flat dishes provided with a cover (petri dish) which have previously been sterilized, and, after the gelatin has hardened, it is set aside for the colonies to develop. This procedure is termed *plating*. Each kind of bacterium that will grow upon the material used, produces a characteristic group or colony.

The colonies are then counted. For example, if 1 cc. of water is used and 100 bacteria developed, the soil contains 100,000 to the gram, since the quantity of water used was shaken with 0.001 gram soil.

The number of bacteria counted in this way in the soil is somewhat variable; from 8,000 to 6,000,000 per cubic centimeter have been found in the surface soil. The number decreases with the depth, until at the 5th to 6th foot comparatively few are found. The following is an example of such a test:

[1] P. E. Brown, Iowa Research Bulletin No. 2.

Inches	Number of bacteria in one gram soil[1]
2	1,330,000
4	1,500,000
6	1,900,000
8	260,000
10	265,000
12	124,000

The number of bacteria so counted appears to have no direct relation to the ammonifying, nitrifying, or denitrifying power of the soil. Important groups of soil bacteria, such as the nitrifying, do not develop colonies at all. The bacterial count appears to be more closely related to the organic matter content than to anything else. If it is desired to study the bacteria further, the desired medium is inoculated with a portion of a colony grown on the plate.

Another method[2] of estimating the number of bacteria consists in inoculating a series of suitable media from different dilutions of the soil, say equal to 1 mg., 0.1 mg., .01 mg., and .001 mg. of soil. Suppose that with ten tubes inoculated from .01 mg. soil, 7 nitrify and 3 do not. Then we estimate that 7 bacteria were present in 10 times .01 mg. soil, or 7,000 are present in a gram. The solution for inoculating is prepared by shaking the soil with sterilized water as described above.

Kinds of Soil Bacteria.[3]—The general tendency of bacterial action in the soil is along well defined lines, although reverse changes occur and complicate the process. Organic matter, by decay or putrefaction, is finally converted into carbon dioxide, water, ammonia or nitrates, and mineral salts. Some soil bacteria produce organic matter from hydrogen or marsh gas and carbon dioxide, or use other inorganic materials (sulphur, or sulphides) as a source of energy, but, in spite of this, the general movement is as indicated. The general movement of organic nitrogen is towards the form of nitrates, through ammonia, in spite of the presence of bacteria which act in the reverse direction and con-

[1] Chester, Delaware Bulletin No. 65.

[2] Wiley, Principles and Practice, Agr. Chem. Anal., Vol. 1.

[3] Kansas Bulletin 117; New Jersey Bulletin 40.

vert nitrates into ammonia or bacterial substances, or ammonia into bacterial substance. Under special conditions favorable to the growth of the bacteria concerned, these reverse tendencies may predominate, or develop to such an extent as to materially modify the final results.

The bacteria which affect the soil nitrogen are very important. Stoklosa[1] divides the bacteria into seven groups with respect to their action towards nitrogen:

(1) Bacteria which decompose nitrogenous organic bodies and produce ammonia.

(2) Bacteria which oxidize ammonia to nitrites.

(3) Bacteria which oxidize nitrites to nitrates.

(4) Bacteria which reduce nitrates to nitrites and ammonia.

(5) Bacteria which reduce nitrates to nitrites and the latter to elementary nitrogen.

(6) Bacteria which change ammonia, nitrites or nitrates into protein or bacterial body substance. This includes members of all the other groups.

(7) Bacteria which fix atmospheric nitrogen and use it to form compounds.

Bacteria have been found in the soil which take oxygen from sulphates, thus reducing them. Other bacteria are found which oxidize hydrogen sulphide to sulphates.

As regards organic carbon there are two great classes of bacteria:

(1) Those which oxidize organic carbon and produce carbon dioxide.

(2) Those which reduce organic carbon and form marsh gas and solid products. Bacteria are also found in the soil which can utilize carbon dioxide and hydrogen to form organic matter, and there are also some which can use marsh gas. Bacteria which require oxygen are called *aerobic,* those which do best without oxygen, *anaerobic.*

Ammonification.—A large number of different bacteria and molds are capable of converting organic nitrogen into ammonia.

[1] Bulletin 94, p. 193, Office Exp. Sta.

Molds probably do the larger portion of the work in manure heaps and very peaty soils, but in ordinary arable soils bacteria predominate. Most of the bacteria which grow upon gelatin or agar are ammonifying.

Bacterium mycoides, which appears to be the most important, decomposes albumen with the production of ammonium carbonate and small quantities of formic, acetic, and butyric acids, carbon dioxide, and other products. It requires the presence of oxygen; otherwise it reduces nitrates, if present, to nitrites or ammonia. The optimum conditions for its activity are a temperature of about 30°, complete aeration, slightly alkaline medium, and a slight concentration of the nitrogenous substance in solution.

The moisture and temperature conditions of the soil play a prominent part in determining the character of the bacterial flora, and hence also the character of the chemical products formed. The mechanical and chemical constituents of the soil are also of decided influence. Heavy clay or loam soils contain a greater number and variety of anaerobic organisms than light sandy or sandy loam soils under the same conditions. But aerobic and anaerobic bacteria are found in both kinds of soils. Aerobic organisms may produce conditions favorable to the growth of anaerobic organisms. Ammonification in the soil is due, at times, to processes partaking largely of the nature of decay, and at other times of putrefaction. By decay we mean the complete volatilization of the organic matter, while in putrefaction ill-smelling bodies are found.

Study of Ammonification.—Ammonification may be studied in culture solutions, or in soils. The former is better adapted to certain bacteriological studies, but methods which involve the use of the soil approach more closely to natural conditions. In either case, at the end of a definite period of time, the extent of the process is compared by an estimation of the quantity of ammonia formed.

Brown,[1] for example, uses a culture solution composed of 10

[1] Iowa Station Research Bulletin No. 2.

grams. peptone in 1,000 cc. distilled water. He shakes 100 grams. soil with 200 cc. water, filters, and inoculates 100 cc. of the sterilized culture solution with 20 cc. of the filtrate. Ammonia is determined in the culture after incubation for six or seven days. When soil is to be used as a culture medium, 100 grams. air-dried soil are mixed with 5 grams. dried blood or 5 grams. cottonseed meal and 5 grams. water and inoculated with 20 cc. soil infusion, and incubated as before.

Various conditions which affect the process of ammonification can be studied in this way, such as the temperature, character of medium, time of incubation, kind of bacteria, etc. If pure cultures of different bacteria are compared, it is of course necessary to estimate the number of bacteria in the liquid used for inoculation, according to the method already outlined. Two important ammonifying bacteria are Bacillus mycoides, and Proteus vulgaris, but a large number of bacteria take part in this process.

The *ammonifying power* of the soil has been defined by some workers as the quantity of ammonia produced on inoculating a definite quantity of a suitable culture medium with a definite quantity of soil, and incubating under definite conditions. Ammonifying power measured in this way depends upon the number and activity of the bacteria in the soil at the time of inoculation, and will be affected by anything which affects them, such as the soil temperature, its moisture, kind and quantity of food present, character of soil, etc. In carrying out such tests, it is exceedingly important that the soils studied be kept under comparable conditions as regards these varying factors, so that only one factor, the one being studied, is variable. Ammonification in soils is, however, quite different from ammonification in solution.

Nitrification.—Nitrification takes place in two stages: nitrates are first formed from ammonia, and then changed to nitrites, Two kinds of bacteria have been isolated, namely, the nitrous and the nitric organisms.

The bacteria which oxidize nitrites to nitrates may be isolated from the soil without any great difficulty.[1] A solution is prepared as follows:

[1] Wiley's Principles and Practice of Agricultural Analysis, Vol. I.

Distilled water	1,000 cc.
Potassium phosphate	1 gram
Magnesium sulphate	0.5 "
Calcium chloride	trace
Potassium nitrite	0.2 gram

After sterilization, 100 cc. of the solution is inoculated with about 0.1 gm. moist soil. This medium is unfavorable to all bacteria except the nitrate organism. After the nitrate organism

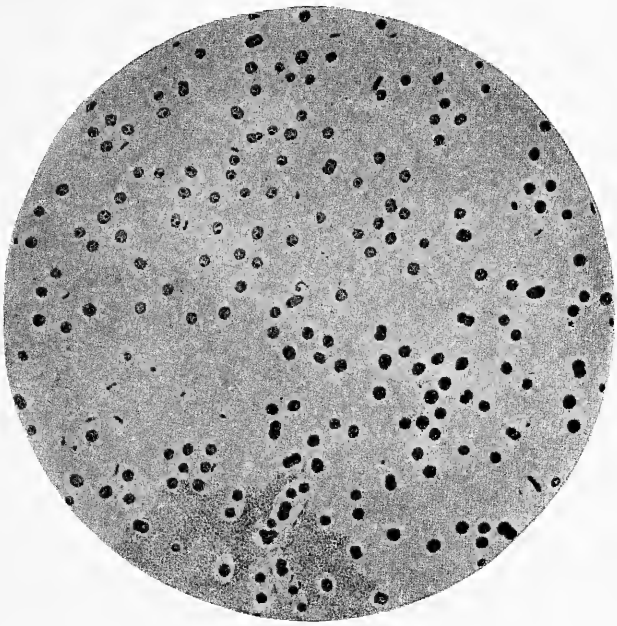


Fig. 49.—Microscopic appearance of nitrous bacteria. Winogradski.

has developed, as shown by the formation of nitrates and the weakening or disappearance of the nitrous acid, a few drops of the culture are diluted with sterilized water, and fresh portions of the medium seeded with single drops of the diluted culture. Some of these cultures will probably contain only the nitrate organism, but at any rate, the other bacteria can be eliminated by a few more cultures. The purity is tested by *plating* with a drop from each culture. The nitrate organism does not

grow on gelatin or agar, so that if no colonies appear, the solution is probably free from contaminating bacteria. The growth of these organisms produces scarcely any change in the appearance of the solution. After staining with coloring matter, the organisms may be seen under the microscope as minute, peanut-shaped bacteria. They are termed *Nitrobacter*.

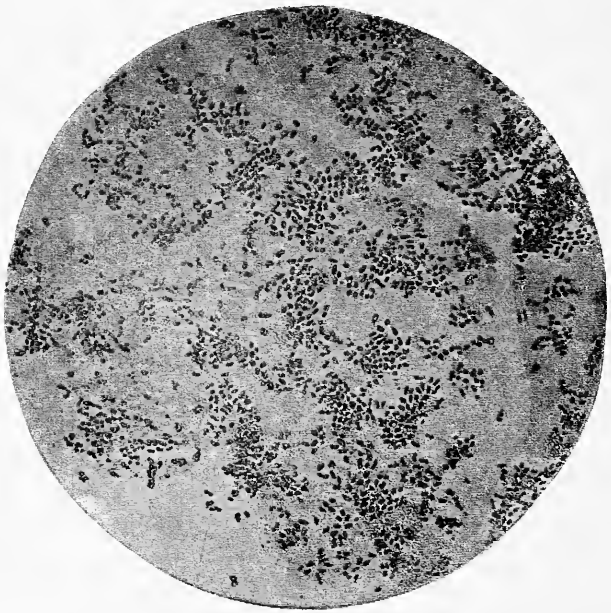


Fig. 50.—Microscopic appearance of nitric bacteria. Winogradski.

The nitrous organism, which converts ammonia to nitrites, is much less easily isolated than the nitric organism, for the reason that other bacteria will grow along with it, and also because it does not grow well on agar or gelatin plates. Winogradsky[1] was finally successful in isolating it. He first cultivated the bacteria in a medium of the same composition as that given above, except the potassium nitrite was replaced by about 2 parts per thousand of ammonium sulphate. A little magnesium carbonate

[1] Wiley's Principles and Practice, Vol. I.

was also added. Silica medium was prepared by treating water glass (sodium silicate) with hydrochloric acid, and dialyzing in distilled water until free from salts. The solution of silica was then concentrated, nutrient salts added (in proportions referred to above), and the liquid seeded with one drop of the culture mentioned above. The mixture was poured into a sterilized petri dish, and a drop of a saturated solution of salt added to coagulate the silica. This mineral jelly was very unfavorable to the growth of any except the nitro-organisms.

The bacteria grow as very small colonies, but on the surface they form a white crust. Stained with dye, and examined under the microscope, they appear as round or roundish organisms. Winogradsky separated three varieties of nitrous bacteria: Nitrosomonas europaea from Europe, Nitrosomonas javanesis from Java, and Nitrosococcus from America.

Study of Nitrification.—Nitrification may be studied in culture solutions, or in the soil, and each method has its advantages for certain kinds of work.

A culture solution may be prepared as follows:[1]

Distilled water	1,000 cc.
Ammonium sulphate	2.0 gram
Potassium phosphate	1.0 "
Magnesium sulphate	0.5 "
Ferric sulphate	0.4 "
Sodium chloride	2.0 "

To each 100 cc. portion, 1.0 gm. magnesium carbonate is added. The solution is inoculated with a small amount of soil, or with soil extract, and incubated for 25 to 50 days. The quantity of nitrous and nitric nitrogen is then estimated. This method may be used for studying the effect of temperature, light, etc., or for estimating the inoculating power of soils held under different conditions. The differences in the effect of soils inoculated into different solutions will, of course, be due to differences in the number and activity of the organisms in them.

[1] Lipman, Report New Jersey Exp. Sta., 1907, p. 176.

If a soil is to be used,[1] it is mixed with a small amount of ammonium sulphate, cottonseed meal or some other nitrogenous material, and water. Fresh moist soil may be used, or air-dry soil, which is inoculated with other soil to furnish the bacteria. It is hardly practical to sterilize the soil by heat, as this changes its chemical character decidedly. After incubation for a period of 30 to 50 days, nitrates are estimated in the soil. Nitrification in the soil is different from nitrification in solution. Cottonseed meal added to a soil will nitrify, while if added to solution, it will putrify.[2]

Nitrification, ammonification, and similar soil activities, may be studied with respect to the soil, or with respect to the organisms.[3] *Nitrifying capacity*[4] may be defined as the capacity of a soil to serve as a medium for the growth of nitrifying organisms, compared with a standard soil, both soils being provided with equal members of bacteria of the same activity, with equal amount of nitrogenous compounds, and kept under similar conditions. *Nitrifying power* may be defined as the ability of a soil to set up nitrification in a soil or culture medium inoculated with it, and is a measure of the number and activity of the organisms in the soil. Similar terms may be applied to other bacterial activities.

Conditions Favorable for Nitrification.—The conditions favorable for the development of the nitrifying organisms, as established by experiments, are as follows:

(1) *Suitable Food.*—Potash, phosphoric acid, lime, sulphates, and carbon dioxide appear to be essential.

(2) *Presence of Base.*—The nitric acid must be neutralized, as the organisms will not thrive in an acid medium. Calcium carbonate or sodium bicarbonate are effective. Too much base is injurious.

(3) *Suitable Temperature and Moisture.*—Nitrification is most active at 36°. It almost ceases at low temperatures.

[1] Am. Chem. Jour., 1903, p. 225

[2] Report North Carolina Exp. Sta. 1902-3, p. 27.

[3] Stevens and Withers, Proc. Ass. Off. Agr. Chem., 1909, p. 34.

[4] Texas Bulletin, 106.

(4) *Absence of Strong Light.*—Light suspends the action of the organisms and finally destroys them.

(6) *Freedom from Excess of Salts.*—Ammonia chloride, carbonate, calcium chloride, or other salts in excessive amounts inhibit its action.

Physical Conditions.—The three most important physical condition which affect nitrification are, looseness of the soil, temperature, and water content.

A loose and porous condition of the soil is more favorable to nitrification than a compact condition. Thus, a soil under cultivation allows more nitrification than the same soil in pasture. Stirring a soil also favors nitrification. For example, King obtained the following results in 285 days:

	Nitric nitrogen per acre foot	
	Cultivated weekly	Cultivated every two weeks
	Pounds	Pounds
Not cultivated	326	326
Cultivated one inch	218	213
Cultivated two inches	323	199
Cultivated three inches	441	401
Cultivated four inches	387	245

The temperature also has a decided effect upon nitrification, as is shown by the figures of King and Bertz obtained in 27 days, expressed as nitric nitrogen in parts per million of soil.

Temperature degrees F.	Parts per million
34	6.5
50	7.7
70	14.3
90	29.1

Nitrifying organisms, like other living things, have a minimum, maximum, and optimum temperature of existance. The minimum seems to be about the freezing point of water, and the maximum about 45° C., the optimum about 35° C.

Production of Ammonia and Nitrates in the Soil.—The production of active nitrogen in the soil depends upon the nature of the

soil, and the conditions surrounding it. Nitrification and ammonification, if too slow, will not provide the growing plant with sufficient food; if nitrification is too rapid, the excess of nitrates may be washed out and lost, thereby diminishing the productive power of the soil.

The following is an illustration of the effect of moisture:

EFFECT OF WATER ON PRODUCTION OF ACTIVE NITROGEN.[1]

	Soil A Relative production of		Soil B Relative production of	
	Nitric nitrogen	Nitric and ammonia nitrogen	Nitric nitrogen	Nitric and ammonia nitrogen
2/9 of capacity	72	101	135	104
3/9 " "	100	100	100	100
5/9 " "	76	106	189	111
7/9 " "	0	70	16	70
9/9 " "	0	35	18	60

The most favorable amount of water for the production of nitrates in the first soil was 3/9 of its capacity. Little or no nitrification took place when the soil was very wet, though a considerable amount of ammonia was produced. Plants which grow in swamps or saturated soils must secure their nitrogen from ammonia or organic bodies.

Nature of the Soil.—By the nature of the soil is meant the complex of physical and chemical properties which make up the soil properties. Which of these properties are of predominating influence in the production of active nitrogen, remains to be ascertained.

The nature of the soil has a decided effect upon the course of nitrification within it. Different soils when placed under similar physical conditions, and provided with an equal number of nitrifying organisms and the same food for them, produce different quantities of nitrates. The quantity of ammonia and nitrates together which is formed is not, however, so different. The following table shows the differences in some soils in the production of nitrates and ammonia:

[1] Fraps, Texas Station Bulletin 106.

EFFECT OF NATURE OF SOIL ON PRODUCTION OF NITRATES AND AMMONIA.[1]

Soil	Rank based on	
	Nitric nitrogen	Nitric and ammonia nitrogen
74	100	100
77	42	94
73	14	84
75	7	77
76	5	70

We find that while these soils varied from 100 to 5 in nitrifying capacity, the production of active nitrogen (nitrates and ammonia) varied only from 100 to 70. When the production of nitrates alone is considered, the soils vary greatly, but if nitrates and ammonia together are taken, the differences are much smaller. If nitrates are much more valuable to plants than ammonia, these differences are very important, but if there is little difference in the value of the two, soils under favorable conditions do not vary greatly in their power to supply nitrogen from the same organic bodies. According to Russell[2] plants on cultivated soils probably absorb all their nitrogen as nitrates. There is no doubt, however, but that plants have the power of absorbing ammonia, and that ammonia is present in the soil, though ordinarily it is present only in a small quantity.

Effect of Chemical Additions to Soil.—While carbonate of lime as a rule accelerates nitrification, it has little effect upon the total production of ammonia and nitrates together. Its use may result in the production of nitrates in excess of the needs of the crops, and consequent loss of fertility to the soil.

Additions of fertilizing materials to the soil (acid phosphate, sulphate of potash) may increase or decrease the production of nitrates, but they have little effect upon the total active nitrogen produced.

[1] Fraps, Texas Station Bulletin 106.

[2] Soil Conditions and Plant Growth, p. 108.

Nature of the Material.—Some substances are more easily attacked than others by the organisms whose final products are nitrates. While the importance of this fact is chiefly to be considered in reference to organic nitrogenous fertilizers, yet it is necessary to bear in mind that the organic nitrogenous compounds of the soil may vary decidedly in the resistance which they offer to the nitrifying organisms. Probably in any soil, the less resistant compounds are oxidized first, and the remainder at a decreasing rate from year to year, so that the effect is a continual diminishing of the nitrates produced for the use of plants, unless measures are taken to introduce fresh nitrogenous material susceptible to nitrification.

Denitrification.—The term *denitrification* is applied to the destruction of nitrates. If an extract of stable manure is added to a solution of potassium nitrate, and kept at a favorable temperature, the nitrates in time will disappear entirely.

Under certain circumstances the nitrates in the soil are deoxidized with the production of organic bodies, nitrites, ammonia, or even free nitrogen. In the latter case there is a loss of nitrogen from the soil. We have already seen that the bacteria which change organic nitrogen into ammonia require oxygen, otherwise they will take oxygen from nitrates. The conditions favorable for denitrification are as follows:

(1) *Insufficient Oxygen.*—In water-clogged soils, or soils which are so compact that air cannot penetrate them, denitrification will take place.

(2) *Presence of an Excess of Vegetable Matter.*—Cases are known in which a heavy application of manure destroyed the nitrates in the soil, and produced a smaller crop than if no manure had been used. Some believe that the denitrifying organisms introduced with the manure are the cause of the denitrification, but as has been pointed out by Warington and others, farm manure introduces into the soil another factor of importance, namely, a large increase in oxidisable organic matter, and this may favor denitrification both by lessening the gaseous oxygen and by tending to rob the nitrates of their oxygen. Undoubtedly the

organisms are essential to the process, but they cannot thrive unless the conditions are favorable to their activity, whether they are already present in the soil, or introduced in the manure. Such conditions are, either a diminished supply of oxygen, as by consolidation of the soil or by saturation with water, or a very large quantity of oxidizable organic matter.

Lipman[1] determines the "denitrifying power" of a soil by seeding 10 grams. of it into 100 cc. of a neutral solution containing definite amounts of nitrates, dextrose, citric acid, and nutrient salts. When the nitrates have disappeared (in about 10 days); the total nitrogen is estimated in the solution. The percentage of nitrogen lost from the various cultures is taken as a measure of denitrifying power of the soil. The solution used is as follows:

1,000.0 cc. water
2.0 grams magnesium sulphate
2.0 " potassium phosphate
1.0 " potassium nitrate
0.2 " calcium chloride
5.0 " citric acid
2.0 drops 10 per cent. ferric chloride.

Neutralize while boiling with sodium hydroxide and add 2 grams dextrose.

The soil may also be used as a medium in which to grow the bacteria for the study of denitrification.

Assimilation of Nitrates and Ammonia.—By growing plants in the solution of a nitrate, it is easily proved that they have the power to absorb it, and as the plant grows vigorously (when other necessary elements are present), the nitrogen must be in a form to be utilized. The nitrate ion may be completely removed from solution when the other nutrients are present. Plants have also the power to take up an excess of nitrates. Small amounts of nitrates are often found in plants. An instance is on record in which corn took up so much that crystals of potassium nitrate would fall out when the stalk was rapped on a table. Nitrates appear to be a form of nourishment most eminently fitted to all cultivated plants. They are easily and rapidly taken up by plants. All

[1] Report New Jersey Exp. Sta., 1907, p. 179.

compounds of nitrogen placed in the soil tend to change to nitrates.

The absorption of ammonium salts by the roots of plants can be shown in the same way, as for nitrates, namely, by growing plants in solutions containing the salts. There can be no doubt that plants absorb ammonia. To decide whether ammonium salts can serve satisfactorily to produce organic matter, is more difficult, since transformation of the ammonia to nitrates must be excluded. Hampe grew corn in solution containing ammonium salts and other nutrients, which were repeatedly changed to exclude nitrification. The corn was apparently not nourished well at first, but later grew well. Kuhn and Wagner obtained similar results. Muntz deprived a soil of nitrates by washing, fertilized with ammonium salts, and took proper precautions, to prevent nitrification. Corn, beans, barley, and hemp attained a normal development, and their growth could only be attributed to the influence of the ammonium salts used as a fertilizer. Other experiments in the same direction could be cited. We must conclude that ammonium salts, as such, serve as nourishment for plants.[1]

Fixation by Bacteria.—Besides the bacteria which fix nitrogen in connection with legumes, other nitrogen fixing bacteria occur in the soil.

These bacteria are not easily isolated, but may be separated by the dilution method. They may also be separated by plating.[2] The chief nitrogen-fixing bacteria are Chlostridum Pasteurianum and species termed azotobacter. Under favorable conditions, they decompose from 100 to 200 grams sugar for each gram nitrogen fixed.

Nitrogen fixing power is estimated by Lipman[3] by inoculating 100 cc. of the culture solution given below with 10 grams of soil. After incubating 10 days at 28° C. the total nitrogen is estimated, the nitrogen in a portion of the original culture solution having

[1] Jour. Agr. Science 3, p. 179.

[2] Bulletin 66, Delaware Exp. Sta.

[3] Report New Jersey Exp. Sta., 1907, p. 181.

previously been estimated; the gain in nitrogen is a measure of the nitrogen-fixing power.

The culture solution is prepared as follows: Water 1,000 cc. mannite 15 grams; potassium phosphate 5 grams; magnesium sulphate 0.2 grams; calcium chloride 0.02 gram; and ferric chloride, 2 drops of a 10 per cent. solution. The solution is then made alkaline with sodium hydroxide, and sterilized. Brown reports that much more satisfactory results may be secured by the use of a soil as the medium for the culture.

We have as yet no evidence that the quantity of nitrogen assimilated by these bacteria, is of importance under ordinary agricultural conditions.

Experiments at the New Jersey Experiment Station[1] indicate the possibility of the addition of nitrogen to the soil in this way. An analysis of the soil at the beginning and end of two years, together with the estimation of the nitrogen in the crops harvested, showed an undoubted gain of nitrogen.

Assimilation of Elementary Nitrogen by Legumes.—The fact that certain kinds of plants can utilize atmospheric nitrogen was not discovered until about 1882. At that time, Hellriegel[2] demonstrated this fact by experiments described briefly as follows:

Lupine seed were planted in pots of soil which had been heated sufficiently to destroy all forms of life in it, and which had been subjected to analysis so that the exact amount of nitrogen present in the quantity of soil taken was known. All the pots were protected from bacteria and watered with sterilized water. To one series of pots, there was added a small amount of an aqueous extract from a soil in which lupines had grown well. To the other series, no addition was made. When the plants were grown, they were dried, and weighed. The quantity of nitrogen in the plants, and in the soil remaining in the pots, was determined by chemical analysis. As the nitrogen originally present in soil

[1] Report for 1907, p. 168.

[2] Exp. Sta. Record 5, p. 835.

and seed was known, the loss or gain of nitrogen could then be easily calculated. Some results are as follows:

	No addition	Soil extract added
	Grams	Grams
Weight of crop	1.01	40.5
Gain + or loss — of nitrogen	−0.007	+1.05

The experiment showed not only that the lupine could utilize the nitrogen of the air, but proved that the soil extract contained something which brought it about. Observations showed that the lupines assimilate nitrogen only when nodules are present on their roots. Examination of the nodules showed that they contained bacteria, and further experiments, similar to the one described above, proved that plants grown in soil inoculated with these bacteria evolved nodules and attained the power of assimilating elementary nitrogen. By experiments similar to those we have described, it was proved that alfalfa, vetch, clover, cow peas, and other leguminous plants have the power of utilizing the free nitrogen of the air when the proper bacteria are present; but corn, wheat, oats, and most plants other than legumes, can take up only nitrogen in combination.

Formation of the Tubercles.—When a lupine seed is planted in inoculated soil free from combined nitrogen, the plant grows until the nutrient in the seed is consumed, then ceases to grow, and shows all signs of nitrogen starvation. In the meantime, tubercles are forming on its roots. In a few days, it begins to grow vigorously, and appears to possess an abundance of nitrogen. The tubercles themselves pass through three stages. There is first vigorous growth, producing the tubercle filled with large numbers of small, rod-like bacteria; then the bacteria change to bacteriods, assuming a T or Y form; and finally the bacteriods begin to disappear and after a little they are absorbed almost completely by the substance of the plant and the tubercles are left as empty pouches. The plant begins to receive benefit from the

nodules when the bacteria assume the bacteriodal form. That the plant receives nitrogen from the tubercles is shown by analyses by Stoklosa[1] at different stages of growth:

Lupines	Nitrogen in tubercles Per cent.
Flowering stage	5.22
Fruit forming	2.61
Plant mature	1.73

Fig. 51.—Branched bacteria from a clover nodule.

The percentage of nitrogen in the tubercles becomes less as they grow older.

Effect of Conditions on Tubercle Formation.—The conditions here discussed are: (1) nature of the bacteria; (2) effect of fertility of the soil; (3) effect of salts.

Nature of Bacteria.—The more active the bacteria, the less quickly do they assume the bacteroidal form; the stronger the plant, the more easily it causes this change. A strong plant may indeed prevent the entrance of the bacteria into its roots and consequently no nodules will be formed. The nature of the bacteria seems to be modified by the host plant. That is to say, the bacteria in the nodules of one plant may not inoculate other plants very well; it may produce nodules upon them, but not of such size

[1] Exp. Sta. Record 7, p. 922.

or in such numbers as on its parent plant. For example, the alfalfa tubercle bacterium will not readily inoculate red clover at first, but in the course of two or three generations, the bacterium may become accustomed to another plant. It is quite possible, however, that there are several kinds of these bacteria.

Effect of Salts.—Marchal[1] found that, in water culture, the formation of tubercles on peas was checked by solutions of the following strengths: Alkaline nitrates 0.05 per cent.; ammonium salts 0.05 per cent.; potassium salts 0.05 per cent.; sodium salts 0.33 per cent.; calcium and magnesium salts and phosphoric acid favored their production.

Effect of Fertility of Soil.—As a general rule, the more nitrogen can be taken from the soil by the plants, the less is taken from the air. Hellriegel found that the best development and largest number of tubercles are attained in a soil quite free from nitrogen, while if the soil contains very much nitrogen, the formation of tubercles may be entirely suppressed. This is probably due to the fact that the plants are too vigorous to allow the entrance of the bacteria. The following examples are from pot experiments with alfalfa by Hopkins.[2] The difference in the nitrogen in the crops grown in inoculated and in uninoculated pots is taken to represent the gain through the agency of the bacteria.

	Gain per acre Pounds
No addition	46
With lime	33
With lime and nitrogen	8
With lime and phosphoric acid	55
With lime, phosphoric acid and nitrogen	9
With lime and potash	38
With lime, potash and nitrogen	9

In every case the addition of nitrogen to the soil decreases the amount taken from the air. It must not be understood that the crop decreases also. In many cases the crop is larger, but most of the nitrogen in it comes from the soil instead of the air.

[1] Exp. Sta. Record 13, 1017.

[2] Bulletin 76, Illinois Sta.

How the Nitrogen is Assimilated.—There are three possibilities: (1) The bacteria secrete an enzyme which causes the plant to assimilate nitrogen through its leaves; (2) the bacteria assimilate the nitrogen and are then consumed by the plant; (3) the bacteria assimulate nitrogen and give it off as soluble compounds, which are taken up by the plant.

Fig. 52.—Nodules on the roots of the soy bean.

The following facts are related to these theories: (1) As observed by Hellriegel, in a medium free from nitrogen the plant ceases to grow while the nodules are developing, then suddenly begins to grow vigorously as if it had a new source of nitrogen. (2) Young nodules contain more nitrogen than old ones.

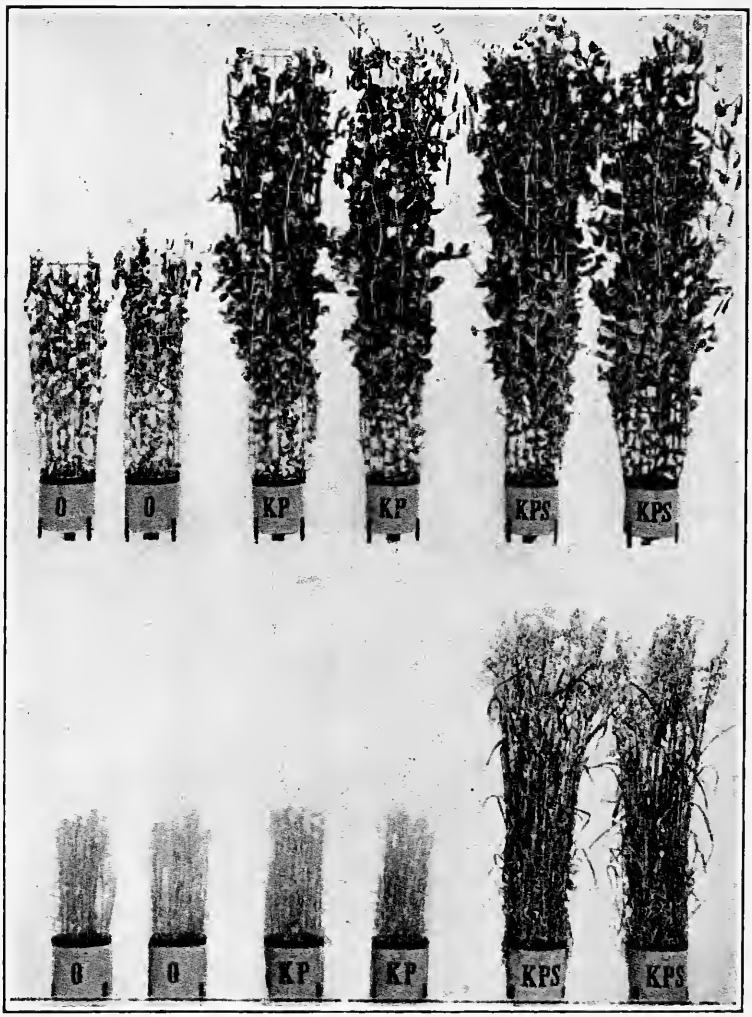


Fig. 53.—Peas without nitrogen (KP) grow as well as with nitrogen (KPS) but oats do not. Wagner.

Further, the plant absorbs the bacteria, and they disappear. (3) Nobbe and Hiltner found that the stronger the plant, the greater the resistance it offers to inoculation, and the sooner the nodules are emptied.

Exactly how the nitrogen is transferred from bacteria to plant is not known.

Inoculation of Legumes.—When a legume is planted in new localities, the bacteria suitable to it may not be present to aid it

Fig. 54.—Showing difference in the growth of alfalfa caused by inoculation with bacteria. Illinois Station.

in the assimilation of nitrogen. The safest plan is to inoculate the soil with the proper bacteria. There are two methods of doing this.

(1) The first method consists in inoculating with soil from a field where the plants have been growing well. This is the surest method, but open to some objections. Freight charges on the soil may be expensive; the soil may be difficult to secure; injurious insects or diseases or weeds are likely to be brought into the soil.

(2) The second method[1] consists in inoculating the soil or seed with a pure culture of the necessary organisms. This method was patented in Germany in 1880, but did not prove a commercial success. The method has been modified, and cultures are now upon the market. Pure cultures of the symbiotic bacteria may easily be prepared by inoculating a suitable sterilized culture medium with the bacteria. The bacteria are sent in a sealed tube; before inoculating the seed or soil their number is increased by allowing them to multiply in a large quantity of water provided with necessary salts and sugar. The seed are then soaked in this liquid, dried, and planted, or the liquid is mixed with soil and the soil distributed and plowed under.

The necessary bacteria are so generally distributed that it is often unnecessary to inoculate the soil. They grow not only upon cultivated plants, but also on many varieties of wild plants.

Changes of Organic Matter.—The organic matter in the soil consists of the unchanged residues of plants and animals, and the products formed from them by bacteria and other forms of life. Decay takes place in two directions, according to the presence of an abundance or a deficiency of air.

In the presence of an abundance of air, decay is *oxidation;* the final products are water, carbon dioxide, ammonia, and nitrates, while the mineral material is left in forms which can be assimilated by plants.

In the presence of little or no air, decay is a *reducing* process, oxygen is taken away from nitrates, or the higher oxides of manganese or iron. Gaseous products, such as carbon dioxide, marsh gas, hydrogen, and free nitrogen, are produced in comparatively small quantities and slowly. The organic material is converted into highly resistant bodies which hold their mineral content in forms not assimilable by plants. The vegetable matter is converted into brown substances, partly soluble in water and imparting a brown color to it. The compounds produced are acid substances, somewhat antiseptic in nature and retard the decay of the vegetable matter. The oxygen required for the production of

[1] Progress in Legume Inoculation, Farmers' Bulletin 315, U. S. D. A.

carbon dioxide comes partly from easily reducible substances containing it, partly from the substance itself. In consequence of this loss of oxygen, the substance becomes richer in carbon. The following analyses[1] of three samples of peat of different ages show this enrichment in carbon:

PERCENTAGE COMPOSITION OF ASH-FREE PEAT OF DIFFERENT AGES.

	Brown peat from surface	Black peat at 85 inches	Black peat from 170 inches
Carbon	57.75	62.02	64.07
Hydrogen	5.43	5.21	5.01
Oxygen	36.02	30.67	26.87
Nitrogen	0.80	2.10	4.05
Ash	2.72	7.42	9.16

The older the peat, the richer it is in carbon and also in nitrogen.

Conditions of Decomposition of Organic Material.—Various experiments have been made to study decomposition of the organic matter of the soil. Many experiments have been carried out by Wollny[2] with the following method: A mixture of sand or earth and the organic material was placed in U tubes, moistened with water, and kept in a constant temperature bath. The carbon dioxide formed was drawn out every 24 hours and collected in a solution of barium hydroxide of known strength. The unused barium hydrate was treated with standard acid, and the quantity of carbon dioxide evolved calculated.

The following are some of the results of these experiments:

(1) *Effect of Ratio of Organic Matter to Soil.*—Varying quantities of powdered horse dung were added to the same quantity of sand, other conditions remaining the same. The oxidation was decreased when the carbon dioxide formed exceeded certain limits, and was less rapid, the greater the proportion of organic substance.

(2) *Effect of Fineness of Division.*—These experiments were made with peat and with pea straw of different degrees of fine-

[1] Detmer, Landw. Versuchs-stat., 1871.

[2] Die Zersetzung d. Organischen Stoffe.

ness. The finer the more difficultly decomposed substance, the more rapidly it oxidized. Easily decomposed substances, pea straw for example, did not oxidize more rapidly when finely divided.

(3) *The Stage of Decomposition of the Material.*—The more decomposed the substance, the less rapidly it is oxidized. The following figures are some results of Wollny:

	Volume of carbon dioxide per 100 volume of soil atmosphere
Cattle manure, fresh	13.43
Cattle manure 8 weeks old	11.71
Cattle manure 20 weeks old	8.25
Peat 0-8 inches deep	2.93
Peat 9-19 inches deep	2.72
Peat 19-31 inches deep	2.55
Peat 31-43 inches deep	2.39
Peat 43-55 inches deep	2.26

It is natural to expect the more easily oxidized material to disappear rapidly, and the more resistant materials at a slower rate.

(4) *Chemical Composition.*—Leguminous straws, on account of the presence of more proteids, are oxidized more rapidly than cereal straws. Waxy material hinders the decomposition of turf; when it is removed by extraction with ether or alcohol, the extracted turf is much more rapidly oxidized than the unextracted. Tannic acid decreases oxidation; rye straw, corn fodder, and soja bean leaves soaked in tannic acid were oxidized less rapidly than the untreated substance. The addition of plant food may accelerate the oxidation.

(5) *Animal residues* oxidize more rapidly than vegetable residues. Green materials oxidize more rapidly than the same material dried and moistened.

(6) *The oxidation* decreases with the *supply of oxygen*, though not proportional to the supply; when the supply decreases beyond certain limits, the oxidation drops rapidly.

(7) *Temperature.*—The relative effects of different temperatures is shown by the following experiment on a compost mixture:

Temperature. Degrees C.	Relative amount of carbon dioxide
10	2.8
20	15.5
30	36.2
40	42.6
50	76.3

(8) *Moisture.*—The oxidation goes on most rapidly at a certain moisture content, which depends on the material. Increase or decrease of moisture causes decreased oxidation.

(9) *Character of Soil.*—The character of the soil has a great effect upon the changes of organic matter. The various factors which affect the decomposition may support or counteract one another, and the effect is due to the predominating quantitative relations. The easy permeability and more rapid warming up of quartz sand are favorable to the decomposition of organic matter, while its low water capacity is a retarding factor. Hence the supply of moisture is the controlling factor in organic decomposition in a sandy soil. In humid regions, the decomposition may proceed so rapidly in such a soil that organic matter does not accumulate to any extent. In a dry climate, decomposition proceeds more slowly than where sufficient moisture is present, but more rapidly in a sand than in other kinds of soil.

Clay soils retain plenty of water, but there is a deficiency of air, and these soils are essentially cold. The decomposition of organic matter in clays is thus determined by the temperature and permeability to air, and proceeds slowly under ordinary conditions. In humid regions, compact clays may exclude the air to such an extent that putrefaction predominates. Heavy rains may discontinue oxidation in clay soils, and bring about deoxidation processes, among them denitrification.

(10) *Vegetation.*—Oxidation of organic matter appears to go on much more rapidly in a bare soil than in a soil covered with vegetation. A straw mulch decreases oxidation, but not as much as a covering of vegetation. The following results of Wollny illustrate this point:

AVERAGE OF 19 SUMMER WEEKS.

	Volume of carbon dioxide in 1,000 volumes air
Under grass	2.1
Under straw mulch	7.2
Bare soil	9.4

The thicker the plants, the greater their effect in reducing oxidation. The following experiment of Wollny show this fact:

Number of plants	Volume of carbon dioxide in 1,000 volumes air
3 oats to 0.1 meter	5.0
6 oats to 0.1 meter	3.4
12 oats to 0.1 meter	2.3
24 oats to 0.1 meter	1.9

The difference appears to be largely due to the drying out of the soil by the plants.

A covering of vegetation thus conserves the organic matter of the soil; cultivation and bare fallow decrease it.

Value of Humus.—The chief chemical action of humus results from its solvent action, and the solvent action of the carbon dioxide which it produces in its decomposition. Water containing carbon dioxide has a much greater solvent power on minerals than pure water. This is illustrated by the following experiments of Dietrich.

MINERAL MATERIAL DISSOLVED BY SOLVENTS.

	Distilled water	Water containing carbon dioxide
	Gram.	Gram
Loam soil	0.039	0.072
Basalt	0.016	0.298
Phosphorite	0.032	0.072
Gneiss soil	0.067	0.340

The addition of humus (turf) to the soil increases its water capacity.

	Water capacity in volume per cent.
Loam	34.4
¾ loam and ¼ peat	39.0
Sand	11.7
Sand ¾ and peat ¼	22.7

Except with soils very rich in humus, the greatest production will be secured only by extensive use of manures rich in organic matter, or other measures suitable to enrich the soil in humus materials.

Action of Carbon Bisulphide on Bacterial Change.[1]—Carbon bisulphide applied to the soil during the growing season may destroy or injure the crop, but if it is applied some time before planting, it increases the fertility of the soil to a decided extent. Its action appears due to its effect on the soil bacteria. In an ordinary soil, the bacteria have reached a condition of equilibrium. Carbon bisulphide destroys or injures the bacteria, and diminishes the production of active nitrogen. In time, new bacteria develop, but along different lines, and there occurs both an enormous increase in number of bacteria, and an abnormal predominance of certain species. The bacteria which prepare active plant food are more energetic, and the fixation of nitrogen also takes place to a greater extent than usual. The nitrogen is at first locked up in the bacterial bodies, and so is useless to the plants, but it becomes active when they decay. Hence the action of the carbon bisulphide is depressing if applied to a growing crop, but it acts like a nitrogenous fertilizer to a succeeding crop. After a longer or shorter time, the soil is more exhausted than it was at first. This is probably due not only to the rapid transformation of the more easily decomposed organic nitrogen of the soil into active nitrogen, but also to the abnormal mixture of soil bacteria due to the changed conditions.

Treating the soil with toluene, and heating the soil, have similar effects to carbon bisulphide. The heat, however, itself changes the chemical composition of the soil, rendering both organic and inorganic material more soluble. According to Russell,[2] the action

[1] Russell, Soil Conditions and Plant growth, p. 114.

[2] Jour. Agr. Science 3, p. 111.

of these agents is due to the destruction of larger forms of life which feed on the bacteria and so keep down their number.

Effect of Additions on Bacterial Changes.—Fertilizers, lime,[1] stable manure, and other additions to the soil affect the bacteria of the soil. In some soils, on fertilization with sodium nitrate, bacteria develop, which change nitrates into ammonia and protein, and which may affect decidedly the utilization of the nitrogen by plants.

Azotobacteria appear to be dependent on the presence of lime and magnesium carbonates; so much so that it has been suggested that this dependence may be utilized for the detection of the need of soils for lime. Liming the soil may thus increase the growth of nitrogen-fixing bacteria.

Active plant food may also affect the bacterial relations. Some bacteria have greater power for securing their mineral nutrients than others. Additions of plant food to the soil may increase the number and activity of certain kinds of bacteria. The bacterial life of soils deficient in active plant food may also be low.

Weeds may have an effect upon the bacterial relations of the soil. Cuizeit, by estimating the nitrifying power of soils seeded to oats alone, and to wild mustard, found that the mustard decreased the nitrifying power of the soil, and the differences persisted the following year. He concluded that the unfavorable effect of weeds such as wild mustard was due not only to unfavorable effects on general conditions of growth, but also to their unfavorable effects on the bacterial content of the soil.

Fixation of Phosphoric Acid and Potash by the Soil.—When a solution of potassium chloride is brought in contact with a soil, and afterwards subjected to analysis, it is found that a portion of the potash has disappeared from solution. This phenomenon is called *absorption*, or *fixation*. Phosphoric acid, organic matter and other bodies, likewise disappear from solution.

Fixation may be studied by bringing a weighed quantity of soil in contact with a definite quantity of a solution of known composition, for a definite time, shaking from time to time and then

[1] Brown, Iowa Research Bulletin No. 2.

withdrawing a portion of the solution for analysis. By keeping all conditions constant except the one to be studied, we may determine the effect of (*a*) the nature of the soil, (*b*) the ratio of soil to solution, (*c*) the concentration of the solution, (*d*) the time, (*e*) the temperature, and (*f*) the nature of the salt used. These are the principal factors which affect fixation.

Another way[1] of studying fixation is to allow a solution of definite composition to percolate through a column of soil, but this method is open to the objection that the solution afforded to different layers of the soil is of different composition, since it becomes progressively weaker as it percolates into the soil. This method is in principle the same as mechanical washing devices, in which fresh water flows where the clean material comes out, and the dirty material enters where the dirty water flows out.

Factors of Fixation.—The important factors governing fixation are as follows:

(1) *The Character of the Salt.*—Potash, phosphoric acid, ammonia, lime, magnesia, and soda are fixed by the soil. Chlorine, nitric acid, and sulphates are not fixed from strong solutions; but from very weak solutions it appears that some fixation may take place.

That is to say, if potassium chloride, nitrate, or sulphate in solution are brought in contact with a soil, a portion of the potash disappears, but the amount of chlorine, nitrate, or sulphate in the solution remains nearly as it was before. The potash is replaced by an equivalent amount of lime, soda, and magnesia.

Different percentages are absorbed when potash, phosphoric acid, etc., are brought in contact with the same soil in equivalent proportions, that is, in the proportion of their combining weights, such as ninety-five parts of potash to 62 parts soda and so on:

$$\underset{95}{K_2O} : \underset{62}{Na_2O} : \underset{56}{CaO} : \underset{39}{MgO} : \underset{34}{2NH_3} : \underset{47+}{1/3P_2O_5}$$

The percentages absorbed are not always in the same order for

[1] Schreiner and Failyer, Bulletin No. 32, Bureau of Soils.

different soils. We give, in the following table, some results secured with 100 grams soil in contact with 250 cc. solution containing 0.07 gram calcium sulphate three days, and equivalent quantities of the other salts:

	Percentage absorbed[1]
NH_3 from ammonium sulphate	60
K_2O from potassium sulphate	55
Na_2O from sodium sulphate	19
MgO from magnesium sulphate	46
CaO from calcium sulphate	26
P_2O_5 from sodium phosphate	17
SO_3 from sodium sulphate	0
Cl from sodium chloride	0

All soils appear to absorb phosphoric acid, potash, and ammonia; but lime, magnesia, etc., are not always absorbed. For instance, Biedermann[2] found that two out of nine soils absorbed lime, six absorbed magnesia, one absorbed sulphuric acid, and all absorbed phosphoric acid and potash.

The form of combination has also some effect upon the amount of absorption. For example, if we compare different salts of potash, such as the chloride, nitrate, and sulphate, we find different amounts of potash absorbed.

	Percentage K_2O absorbed
Potassium phosphate	57
Potassium carbonate	65
Potassium chloride	57
Potassium sulphate	55
Potassium nitrate	51

(2) *The Nature of the Soil.*—Sands, as a rule, have low absorptive powers; loams and clays, much higher. The absorptive power of the same soil depends upon the substance used to measure it. For example, it is different for potash and for phosphoric acid.

In the following table, the absorptive power is measured by the percentage of ammonia absorbed by 50 grams soil from a solution of one gram ammonium chloride in 208 cc. water.

[1] Bretschneider, Jahresber, f. Agr. Chem., 1868, p. 17.

[2] Jahresber, f. Agr. Chem., 1867, p. 77.

Soil	Absorptive power[1]
Norfolk sand	4.0
Tarboro sand	9.8
Norfolk fine sandy loam	10.7
Durham sandy loam	17.5
Porters red clay	17.8
Cecil clay	18.7
Porters black loam	27.5

The black loam in question appeared to be rich in organic matter. With 100 grams soil to 100 cc. solution containing 0.4283 gram potash or 0.3032 gram phosphoric acid, respectively, Biedermann observed a variation in absorptive power from 6.0 to 58.7 per cent. for potash, and 3.1 to 82.2 for phosphoric acid in 22 soils.

(3) *The Concentration of the Solution.*—If the ratio of soil to solution is kept constant, the stronger the solution of salt used, the greater the total amount absorbed, but at the same time the percentage is less. That is, the amount absorbed does not increase to the same extent as the concentration of the solution. The following table illustrates this point:

ABSORPTION[2] OF POTASH FROM POTASSIUM SULPHATE.

Strength of solution (Grams per liter)	Grams absorbed (250 cc.)	Per cent. absorbed
0.4708	0.0609	54.5
0.9420	0.0977	43.5
1.8840	0.1496	33.5
4.7100	0.2360	21.1
9.4200	0.3503	15.7

(4) *Effect of Temperature.*—Increase of temperature sometimes increases absorption of potash but it always increases that of phosphoric acid, according to Biedermann. In the experiment 50 grams soil was used and 100 cc. solution containing 0.3032 gram P_2O_5.

[1] Withers and Fraps, North Carolina Report, 1902-3.

[2] Bretschneider, Jahresber, f. Agr. Chem., 1865, p. 19.

	Amount phosphoric acid absorbed	
	Soil No. 1	Soil No. 2
Ordinary low temperature	0.0065	0.1071
Ordinary higher temperature	0.0941	0.1131
Boiling ¼ hour	0.1768	0.2694
35° C	0.1389	0.2405

Seven additional soils gave similar results.

(5) *Ratio of Soil to Solution.*—Keeping the strength of solution constant, and increasing the weight of soil brought in contact with it increases the total absorption, while the absorption per 1 gram soil decreases.

(6) *Time of Contact.*—Peters[1] studied the time of contact, using 100 grams soil to 250 cc. of solution containing 0.5889 gram potash:

Time	Amount absorbed gram
¼ hour	0.1417
2 hours	0.1571
4 hours	0.1690
8 hours	0.1860
24 hours	0.1990
14 days	0.2037

Absorption of potash takes place rapidly, and is practically complete in 24 hours. Similar experiments have shown that phosphoric acid is absorbed more slowly.

Solubility of Absorbed Material.—Absorbed material has a low solubility in water. Peters[2] estimated it as follows: 100 grams earth was brought in contact with 250 cc. water containing 0.5888 gram K_2O and after 24 hours 125 cc. was drawn off and replaced with water. This process was repeated every 24 hours for 9 days, and each extract was subjected to analysis. The absorbed potash is more soluble in water than the soil potash, but not very soluble—about 1 part in 28,000 parts water under the conditions of the experiment.

[1] Jahresber, f. Agr. Chem., 1860-1, p. 7.
[2] Jahresber, f. Agr. Chem., 1860-1, p. 11.

Water containing carbon dioxide dissolved in 8 days about one-third of the absorbed potash; acetic acid, (1:3), dissolved about two-fifths; and hot hydrochloric acid (1:3 parts water) dissolved all the absorbed potash.

Replacement of Absorbed Material.—If a soil is allowed to absorb one base, and is then subjected to the action of a second solution, a portion of the absorbed base will be replaced by the second base. Other bases in the soil will also enter into solution.

For example, suppose a soil has absorbed potash from potassium chloride. If it be treated with a solution of sodium chloride, some of the soda will be absorbed, and a portion of the absorbed potash, and also some lime and magnesia will enter into solution. Sodium nitrate, ammonium chloride, calcium chloride, calcium sulphate, magnesium chloride, and other salts have a similar action.

The amount of potash displaced would depend upon the quantity present, and the nature and concentration of the salt solution.

Importance of Absorption.—Absorption tends to preserve the potash, phosphoric acid, and ammonia of the soil from being washed out. Soda, lime, and magnesia, for which the soil has less attraction, are more easily washed out. The relative proportion of loss, will, however, depend upon the amounts of these bases present in the soil or rendered soluble. As we have seen in the preceding section, soluble salts of lime, magnesia, or soda decrease the absorption of potash or replace absorbed potash.

Absorption tends also to prevent loss of the soluble plant food placed in the soil in the form of fertilizers; for nitrates, however, the soil appears to possess little absorptive power.

The practical importance of absorption lies chiefly in connection with the application of soluble plant food. It is important to know whether soluble plant food applied to the soil will be washed out and lost. Nitrates are not absorbed. Potash, phosphoric acid, and ammonia, as we have seen, are fixed by the soil, and as the solution percolates through the soil, coming in contact with fresh masses, the larger part of the soluble material

is removed. Thus, even with a soil of low absorptive power, on account of the great mass of soil which enters into consideration, almost all the material is absorbed.

With a soil of good absorptive power, phosphoric acid is mainly retained by the uppermost layers, the first 9 inches; with potash, although the uppermost 9 inches contains chiefly the greater portion of the unused fertilizer, a considerable amount penetrates to and is retained by the second and third 9 inches.

The absorptive power of soils also enters into consideration when the land is to be irrigated, in which case it is desirable to know whether any of the fertilizer may be washed out or carried to too great depth by application of the water, and how long a time should elapse before irrigation will cause a loss of plant food.

Some sandy soils have little absorptive power, and no doubt losses of plant food occur where heavy rains fall shortly after applications of potash and soluble phosphates.

Cause of Absorption.—The causes of absorption are different for the basic radicles, potash, soda, lime, magnesia, etc., and for the acid radicle, phosphoric acid. It is accordingly necessary to consider these two separately.

In offering an explanation for the absorption of bases, we must consider the following facts:

(1) The amount of absorption is often related to the quantity of silicates in the soil decomposed by hydrochloric acid.

(2) When a base is absorbed, it is replaced by equivalent quantities of other bases. Treat a soil with sodium chloride, for example, and the absorbed sodium will be replaced largely by lime, magnesia, soda, and potash.

(3) When a soil is treated with an acid, it loses its absorptive power almost entirely, but the addition of calcium carbonate restores it in great part.

(4) Hydrated oxides of iron, and aluminum, hydrated aluminum silicate, and sand have slight absorptive powers, but not sufficient to account for the absorptive power of soils containing them. Humus has a comparatively high absorptive power, but the small quantity in most soils will not account for the results.

The conclusion is reached that the absorptive power of soils for bases is due to the presence of silicates which react with the substance which it will absorb. The reaction is reversible. The lime, soda, magnesia, and potash of simple or complex silicates enters into reaction with the substance absorbed by the soil, until equilibrium is reached between the solution and the reactive soil particles. We can hardly expect the law of mass action to be followed, for the reason that the absorbing silicates are probably mixtures with different reactivity.

Attempts have been made to explain absorption as physical adhesion to the soil particles. While a portion of the absorbed substance may be held in this way in soils composed of fine particles, this theory does not account for the replacement of the absorbed base by other bases, or for the varying absorptive power of different soils of the same physical composition, or for the loss of the absorptive power of a soil by treatment with an acid, and partial restoration of it by addition of calcium carbonate.

Absorption of Phosphoric Acid.—When a phosphate is brought in contact with a soil, both base and acid will disappear partly from solution. The base follows the laws of absorption as outlined above. The phosphoric acid follows about the same laws, but the cause of the absorption is different, and is due to reaction with basic substances, such as hydrated oxides of iron and aluminium, and carbonate of lime, with production of the much less soluble phosphates of calcium, aluminium, and iron. It is also possible that the phosphates have power to decompose some of the weak silicates. Phosphates are absorbed more slowly than bases.

Changes of Phosphoric Acid in the Soil.—Calcium phosphate, in the presence of aluminium and iron hydroxides, has a tendency to change into phosphates of these bases, which are much less available to plants. The calcium phosphate dissolves, and the solution reacts with the hydroxides in question, forming phosphates which are much less soluble. The presence of calcium carbonate will hinder the reaction, since it also will react with the phosphoric acid in solution.

PHOSPHORIC ACID DISSOLVED.[1]

(1 gram substance to 400 cc. water.)

	Parts per million
From calcium phosphate	43
From ferric phosphate	42
From basic ferric phosphate	33
From aluminium phosphate	58
From basic aluminium phosphate	4

Decaying organic matter, by reducing ferric to ferrous phosphate, and perhaps by combination with the phosphoric acid, tends to render phosphoric acid available.

The slow process of weathering breaks up the complex silicates of the soil grains and releases the compounds of phosphoric acid therein. At the Rothamsted Experiment Station, where wheat has been grown with various fertilizers since 1852, the amount of phosphoric acid soluble in citric acid was as follows, on plots that did, and did not, receive phosphoric acid.

	Pounds per acre		
	1865	1881	1893
No fertilizer	244	192	202
Phosphates	672	853	1,050

The first plot produced on an average 12¾ bushels wheat continuously, but the weathering was sufficient to maintain nearly constant the quantity of phosphoric acid soluble in citric acid. In the other case (producing 24 bushels wheat) the addition of fertilizers made a considerable increase in the soluble phosphates present. The weathering of the minerals constantly releases the phosphoric acid inclosed therein. In the presence of decomposable compounds of iron, and aluminium, there is a constant tendency for the phosphoric acid to change to less soluble forms. Calcium phosphate is dissolved by the soil water, brought in contact with iron and aluminium oxides and unites with these to form phos-

[1] Bureau of Soils, Bulletin, 41.

phates. If calcium carbonate is also present, the distribution of the phosphoric acid will be modified by the quantitative relation between the fixing materials, and the change to iron and aluminium phosphates may be reduced or even reversed.

On the other hand, decaying vegetable matter may reduce ferric to ferrous phosphates, with the production of more soluble bodies.

CHAPTER XII.

SOIL DEFICIENCIES.

Any condition or defect of the soil which tends to prevent the maximum production of crops, or to render it unsuitable for cultivation, may be termed a soil deficiency. Soil deficiencies may be physical or chemical.

Physical Deficiencies.—These are mentioned here merely for the sake of completeness. As regards physical deficiencies, a soil may be too porous or too stiff, too wet or too dry, too cold or too shallow.

Fig. 55.—Experimental plots, Göttingen, Germany, Agricultural Institute.

Cold soils, which are usually wet, when drained become warmer. The depth of shallow soils may be increased by plowing a little

deeper every year or by subsoiling. Both porous and stiff soils are benefited by organic matter, which makes the former less porous and the latter less stiff. Lime may improve stiff soils by making them more pulverulent. Wet soils are improved by underdrainage. Dry soils may be aided by frequent stirring to prevent evaporation of water from them, or by irrigation. Hard pan may sometimes be removed or prevented from forming, by proper plowing, or subsoiling. In some cases it is profitable to use explosives to remove it.

Chemical Deficiencies.—The chief chemical deficiencies of soils are acidity, alkali (excess of soluble salts), deficiency in organic matter, deficiency in lime, and in available plant foods, phosphoric acid, potash, or nitrogen. These deficiencies have been discovered by means of field experiments, aided by other methods of experiment.

Recognition of Chemical Deficiencies.—There are three general methods of ascertaining the probable chemical deficiencies of soils:

(1) Field experiments.
(2) Pot experiments.
(3) Chemical analysis.

Field Experiments.—All soil theories must eventually be tested in the field. Field experiments are, therefore, fundamental, and information secured by other methods must eventually be brought back to the field, and stand the test of actual crop production upon the soil. The more removed from field conditions the work of the investigator, the more careful he should be to bring his results into relation with actual crop production. Unless tested in this manner, theories may be developed which are entirely too far removed from agricultural conditions.

Methods of making field experiments with fertilizers are outlined in Chapter XVI. Similar methods are used in other experiments, arranged according to the information desired.

Field experiments are subject to vicissitudes of weather, insect pests, variations in soil, etc., and hence must usually be carried on for several years, or else on an extensive scale. Unexpected

variations are liable to occur, and this fact must be allowed for in all consideration of the data.

Pot Experiments.—In pot experiments,[1] plants are grown in the soil to be tested, various additions being made to the soil according to the information desired. The soil can be mixed until

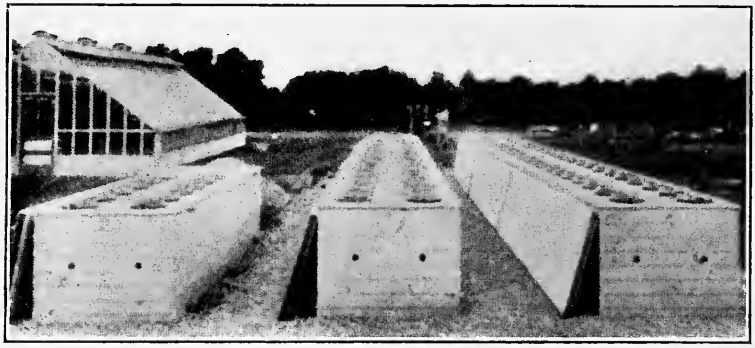


Fig. 56.—Pot experiments. New Jersey Station.

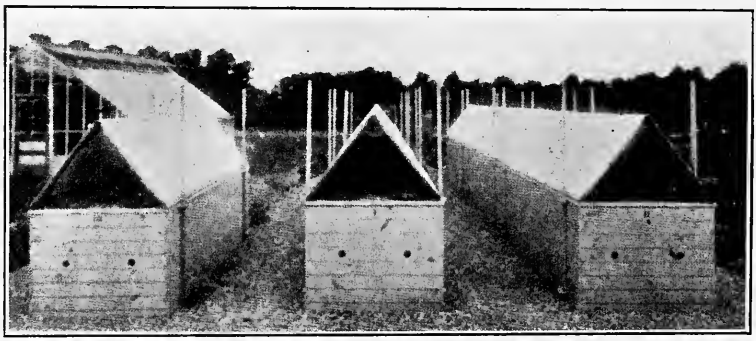


Fig. 57.—Protection of pot experiments from inclement weather. New Jersey Station.

uniform, and the pot supplied with a favorable amount of water, kept at a favorable temperature, and the crops protected from damage by insects, birds, or storms. The conditions can be more

[1] Exp. Sta. Record 7, p. 77; **5**, p. 849.

easily controlled than field conditions, and certain problems can be much more easily studied. Conditions are relatively more favorable than in the field, and the relation between the pot experiments and field results, must be traced out.

The pots used vary much in size, shape, and material. They may be made of glass, galvanized iron, enameled iron, or earthenware, and may vary in size from a few inches in diameter to those which cannot well be handled

Fig. 58.—Pot experiments. New Jersey Station.

and are imbedded in the ground. Galvanized iron is open to the objection that the zinc may corrode and form poisonous compounds. An ordinary form of pot consists of a cylindrical vessel about 8 inches in diameter and 8 inches deep. It first receives a layer of gravel, covering a metal or glass ventilating tube which reaches above the top of the pot. The soil is placed on this, and receives the desired additions. The seed

planted should be of uniform size and vary in moderate limits in weight, such as 41 to 47 mg. each for wheat grains. The seed are often germinated, and the seedlings planted. During the period of growth, the pots are usually weighed at suitable intervals, and sufficient water added to keep the moisture content uniform. The pots are kept in glass houses, in canvas houses, in wire houses, or in the open air on trucks which can be run into a glass house for protection against storms. The pots are also buried in the ground sometimes, but the water content of the soil is much less easily regulated under such conditions. Examples of pot experiments have been given in the text.

The following is the method of procedure used at the Texas Experiment Station:[1]

Washed gravel is added in sufficient amounts to an 8-inch Wagner pot to make the total weight 2 kilograms. Five kilograms of soil are then added. The soil is previously pulverized in a wooden box with a wooden mallet until it will pass a 3 mm. sieve, the gravel being removed.

The addition of fertilizer consists of 2½ grams of acid phosphate, and 10 cc. of solution containing 1 gram nitrate of soda, and 1 gram sulphate of potash. In later experiments 1 gram of ammonium nitrate was used in place of nitrate of soda. If the size of the crop appears to render it necessary, more nitrate of soda or sulphate of potash is added to the pot, the solution being diluted with about 200 cc. of water.

The seed are weighed out so that each pot receives the same amount of seed within 0.1 of a gram. Water is added to one-half the saturation capacity of the soil. If this quantity is found to be too great, it is afterwards reduced, but this is the case in only a few instances. The pots are weighed, placed on scales three times a week, and water added to restore the loss in weight. If the plants need water between weighings, such quantity is added as appears necessary. The object of the weighing is to maintain as closely as possible a constant amount of water in the soil. These pots are kept in a house with glass roof, and canvas

[1] Bulletin 126.

sides and top, for protection against heat, storm, and insect pests.

Wire basket experiments[1] are made in baskets of wire netting, about 3 inches in diameter and 3 inches high, filled with about 200 grams soil, and dipped into melted paraffin. The surface of the soil is covered with paraffined paper, excepting for an opening to admit the seedlings. The pots are weighed daily, and the loss of water restored. The plants are grown for about three weeks.

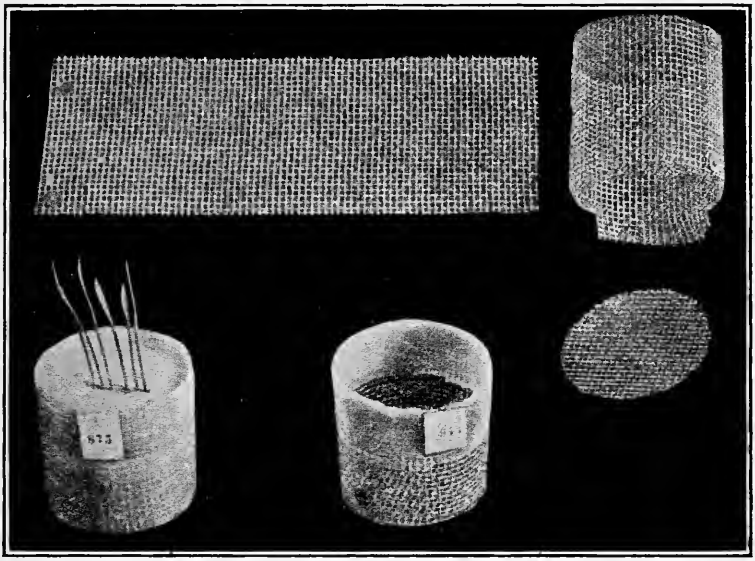


Fig. 59.—Construction of wire baskets. Bureau of Soils, U. S. D. A.

Since air is excluded from the soil and since the seedlings develop for the most part from the material in the seed, these experiments are more remote from field experiments than ordinary pot experiments; still greater caution, therefore, should be exercised in interpreting the results. According to the work of the Rhode Island Station,[2] this method does not give the same results at different times, and the results do not agree with those obtained in field practice.

[1] Whitney, Farmers Bulletin No. 257.

[2] Bulletin 131.

Water culture experiments have been previously described (Chapter II), and are well suited to certain purposes of experiment. They have been used to a certain extent for studying soil deficiencies, by growing the plants in an aqueous extract of the soil. Conditions in water culture are radically different from those in the soil, and still greater caution must be exercised in applying conclusions secured by this method of experiment to the soil. It is quite possible that materials will be injurious in water culture which are innocuous in the soil. Hence it is necessary to confirm conclusions drawn from experiments made in this way by pot and field tests.

Chemical Analysis.—Chemical analysis can be used for the detection of certain soil deficiencies, such as acidity, and the quantity of alkali present. Chemical methods can also be used to form an opinion as to the needs of the soil for phosphoric acid, potash, and nitrogen, as shown in Chapter IX. Chemical analysis is also useful in extending the conclusions from field experiments and pot experiments to other soils under similar conditions.

Acid Soils.—Acid soils contain free inorganic or organic acids or acid salts, which therefore give it an acid reaction. In some cases acidity is due to the decomposition of the remains of plants in the soil, forming organic acids, but it may also be due to inorganic acids.

The acidity of soils is usually neutralized by lime. A soil which receives benefit from lime is not necessarily an acid soil, as lime has other effects than that of correcting acidity; it makes the phosphoric acid more available, liberates potash, increases nitrification, and changes the physical properties of the soil.

Plants behave differently towards acid soils; some receive benefit from liming, while others do not. The Rhode Island Experiment Station[1] has conducted a large number of experiments on an acid soil, limed and unlimed, with the addition of acid phosphate, muriate of potash and sulphate of magnesia, and nitrate of soda or sulphate of ammonia. These experiments, begun in 1893,

[1] See their reports and bulletins; also Veitch, Bulletin 90, p. 183, Bureau Chemistry, U. S. Dept. Agr.; Bulletin No. 66, Maryland Exp. Sta.

were conducted upon permanent experiment plots of the Rhode Island Station. Air slaked lime was applied in 1893 to two of the plots at the rate of 5,400 pounds per acre, and 1,000 pounds in 1894, and none since. Equal quantities of potash, phosphoric acid, and nitrogen have been applied annually to each plot, and, since 1899, sulphate of magnesia. Two of the plots receive nitrogen as sulphate of ammonia, and two as nitrate of soda. The tendency of the two plots which receive sulphate of ammonia is to become

Fig. 60.—Bare spot in barley caused by acid soil. Woburn, England.

acid, since removal of the nitrogen leaves sulphuric acid; while the latter two plots tend to become basic, since the residue left is soda.

Equal numbers of plants were set out on each plot. A great number of different crops have been grown at various times. A few results are as follows:

Plot number	Treatment	Asparagus (pounds)	Barley (pounds)	Onion (pounds)	Turnip (pounds)
23	Sulphate of ammonia	0.0	0.7	0.2	2.5
25	Sulphate of ammonia limed	3.4	6.5	41.5	35.5
27	Nitrate of soda	1.1	2.6	24.0	38.0
29	Nitrate of soda limed	4.7	7.5	44.3	44.0

The acid soils (Nos. 23 and 27) give smaller yields with these crops than the limed soils. The nitrate of soda plot, which, as stated, has a tendency to become basic on account of the basic residue left when the nitrogen is taken up, gives better yields than the ammonium sulphate plot, which has a tendency to become acid.

Effect of Lime on Crops an Acid Soil.[1]—*Benefited by Lime.*—The following gives the ascertained effect of lime on various crops as found by experiments such as described above:

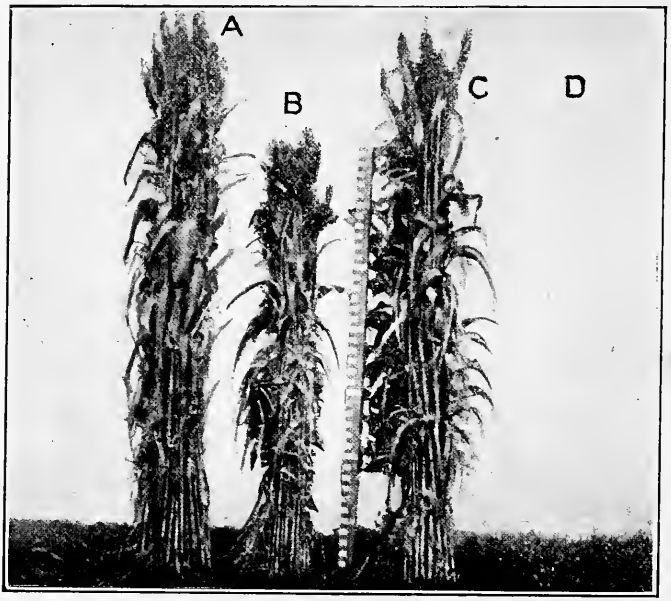


Fig. 61.—Sorghum on acid soil, (A) limed and nitrate of soda, (B) unlimed and nitrate of soda, (C) limed and sulphate of ammonia, (D) unlimed and sulphate of ammonia. Rhode Island Station.

Alfalfa, asparagus, barley, beets, clover, celery, cauliflower, currants, cabbage, cucumbers, corn, lettuce, mangelwurzel, onions, okra, oats, peas, peanuts, pepper, parsnip, pumpkin, sorghum, salsify, seed fruits, stone fruits, squash, spinach, sugar beets, salt bush, timothy, and tobacco.

[1] Wheeler, Farmers Bulletin No. 77, U. S. D. A.

Indifferent to Lime.—Blackberries, millet, potatoes, raspberries, rye, and red top grass.

Injured by Lime.—Cranberries, cowpeas, sheep sorrell, lupine, serradilla, and watermelon.

In these experiments, it will be noted that the plants were supplied with an abundance of phosphoric acid, potash, and nitrogen. Such being the case, the beneficial effect of the lime could not be to render potash or phosphoric acid available. Other experiments showed that caustic magnesia, or sodium carbonate also had a good effect. These substances would also neutralize acidity.

Detection of Soil Acidity.—The most satisfactory method of ascertaining whether a soil needs lime is to determine the gain in crop by its application. It does not necessarily follow that a soil which responds to lime is acid.

The tests for acidity used at present are as follows:

1. *The Litmus Test.*[1]—The soil is moistened with water and brought in contact with blue litmus paper. If acid, the litmus turns red. Carbonic acid also reddens litmus, but to a less degree than an acid soil.

2. *Ammonia Test.*[2]—The soil is treated with ammonia water, and if the liquid assumes a dark brown or black appearance, the soil may be acid. This test applies only where the acidity is due in a considerable measure to acid organic substances, and may not apply to all sections of the country.

3. *Salt Method.*[3].—The soil is shaken with a solution of potassium nitrate and the solution, after being boiled to remove carbonic acid, titrated with caustic soda and phenolphthalein. Part of the acidity is due to formation of aluminium and iron chlorides, which are decomposed in the titration.

4. *Lime Water Method.*[4]—The soil is treated with standard lime water, evaporated, taken up with water, and the filtrate tested by evaporating it nearly to dryness with a few drops of phenolphthalein. If the phenolphthalein indicator becomes pink,

[1] See Circular No. 71, Bureau of Plant Industry.

[2] Bulletin 62, Rhode Island Exp. Sta.

[3] Proceedings Association Off. Agr. Chem., 1902.

[4] Jour. Am. Chem. Soc., 1902, p. 120.

an excess of lime water has been used. If it does not become pink, the soil is still acid. A number of tests are made, so as to ascertain two quantities of lime water, with one of which the soil is acid, by the other, made alkaline. This appears to be a good method.

Other Effects of Lime.—We have already seen that lime is necessary to plant life. Cereal grasses require from about ¼ to ½ as much lime as potash, while leguminous plants take up as much lime as potash, if not more. Lime is usually considered as present in abundance in the soil, but it is quite possible that some soils, especially sandy soils do not supply a sufficient quantity of active lime for the use of certain leguminous plants.

The following is a brief summary of the part which lime (chiefly in the form of carbonate) plays in the soil[1]:

1. It flocculates clay particles, making the soil more crumbly and, with better tilth, more retentive of water and more easily penetrated by rain.

2. It aids growth of bacteria which convert organic nitrogen to nitrates, those which assimilate nitrogen and other bacteria.

3. It neutralizes acids and maintains the soil in an alkaline condition, which is the condition most favorable to the majority of cultivated plants.

4. It makes a soil productive which contains relatively small quantities of plant food.

5. It counteracts the deleterious effect of an excess of magnesia in the soil.

6. It liberates potash in the soil.

7. It unites with phosphoric acid, preventing it from forming less valuable phosphates of iron and alumina.

An excess of carbonate of lime may prove injurious to some plants, notably grape vines and citrus plants. From eight to twenty per cent. of lime may have this effect.

Carbonates of magnesia may, to a certain extent, act in the same way as lime. We have already seen that it is well for lime

[1] See Kellner, Landw. Versuchs-stat., 1896, p. 210.

to have a certain ratio to magnesia. An excess of either lime or magnesia is not desirable.

Lime Compounds in the Soil.—Lime is found in the soil as the carbonate, sulphate, humate, and various more or less complex silicates. Calcareous soils contain considerable amounts of carbonate of lime. It is quite probable that some soils rich in humus contain fair amounts of calcium humates. As a rule, the lime is present in the form of silicates, which are more or less resistant to the action of acid and weathering agencies.

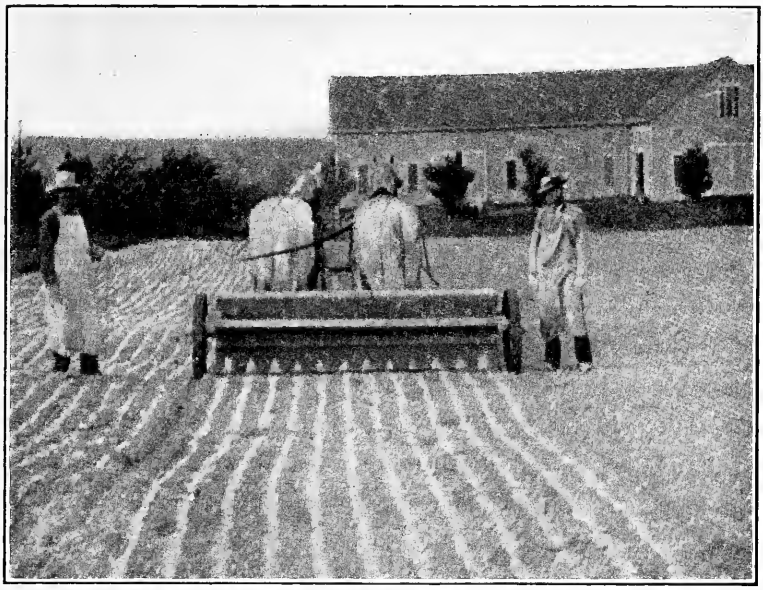


Fig. 62.—Distributing lime. Ohio Station.

Application of Lime.[1]—Lime is applied to the soil as (*a*) *Land plaster* or gypsum, $CaSO_4\ 2H_2O$ which has no power to counteract acidity; (*b*) *Quicklime CaO,* which is the most active form of lime. It is usually slacked before it is worked into the soil. It soon takes up carbon dioxide, and changes into the carbonate. It is made by heating the carbonate, and so is often called burned

[1] Bulletin 159, Ohio Station; Wheeler, Farmers Bulletin No. 77.

lime. (*c*) *Ground Limestone*: Ground limestone is more mild in its action than quicklime and can be used in larger amounts. The finer it is ground, the more effective it is.

$$\underset{\text{Lime}}{CaO} : 56 : \underset{\text{Limestone}}{CaCO_3} : 100$$

One hundred parts of pure limestone contain 56 parts lime, equivalent to 56 parts of pure burned lime. (*d*) *Oyster Shells*: Oyster shells contain some plant food. They may be applied unburnt and burnt. (*e*) *Marl* contains less lime than shells. All forms of lime should be applied some weeks before planting.

Quick lime is applied as a top dressing on land at the rate of 200 to 500 pounds per acre. Excessive applications of lime are injurious. Ground limestone is used in larger quantity, particularly when alfalfa is to be planted. One or two tons per acre of ground limestone may be used every four to six years; even as much as ten tons may be applied.

Lime Liberates Potash.—Lime releases absorbed potash, making it more readily available to plants. *Hence* the lime would act as an indirect potassic fertilizer. Boussingault[1] found the following amounts of potash and lime removed by clover from a limed and an unlimed soil, in Kg. per hectare.

	Potash	Lime	Phosphoric acid
Unlimed, first year	26.7	32.2	11.0
Limed, first year	95.6	79 4	24.2
Unlimed, second year	28.6	32.2	7.0
Limed, second year	97.2	102.8	22.9

It does not follow from the above experiment that the lime "released" potash. The liming made conditions more favorable for the clover, and a larger crop was produced, with a heavier draft on the soil. The availability of the plant food was not necessarily changed because more of it was withdrawn from the soil.

It appears to be generally conceded that lime releases potash,

[1] Storer, Agriculture.

though the writer has been able to find little experimental evidence that such is the case under actual field conditions. In the section on *absorption,* evidence is given that in the laboratory, lime and other salts replace absorbed potash.

Experiments with Burned Lime or Ground Limestone.—In experiments at the Pennsylvania and at the Maryland Experiment Station,[1] ground limestone has given better results than burned lime. At the Pennsylvania Station, lime was used in a four year rotation of corn, oats, wheat, and hay, at the rate of two tons per acre of burned lime every four years or two tons of ground limestone per acre every two years. The average yield for 20 years is as follows:

	No lime	Burned lime	Ground limestone
Corn, bushels per acre	40.9	34.9	39.9
Oats, bushels per acre	33.9	30.9	36.7
Wheat, bushels per acre	13.9	15.9	16.5
Hay, tons per acre	12.5	11.8	14.6

The burned lime injured the corn, oats, and hay, while the ground limestone was of benefit to the oats, wheat, and hay. Analysis of the soil showed that the soil receiving burned lime had lost more nitrogen than the other.

At the Maryland Experiment Station, different kinds and amounts of lime were applied to various plots at the beginning of the experiment. The results of 11 years test with 1,400 pounds of burnt lime, or an equivalent amount of carbonate of lime from shell or marl, with the rotation of corn, wheat, and hay, are as follows:

	No lime	Burned lime	Carbonate of lime
Corn, bushels per acre	24.5	32.0	37.0
Wheat, bushels per acre	10.7	11.0	14.1
Hay, tons per acre	0.65	0.85	1.07

[1] Report for 1902.

Here also the carbonate of lime gave better results than the quicklime.

Salt.—Salt is used to some extent as an application to the soil. It acts as an indirect fertilizer.

Gypsum or sulphate of lime $CaSO_4\ 2H_2O$, is used to a small extent at present. Formerly it was held in high esteem, but at present, preference is given to lime, limestone, or direct fertilizers.

Toxic Substances.—It is possible that some soils may contain injurious substances besides alkali or acids. The theory of Whitney and Cameron, that plants excrete toxic substances, has already been discussed.

Sulphur.—The amount of sulphur[1] in plants has been for a long time under-estimated. Recent work[2] has shown that many plant products (especially seeds) contain much more sulphur than was once thought. Most soils contain only small quantities of sulphur. It is therefore quite possible that some soils are deficient in sulphur. It is possible that the sulphates contained in acid phosphate are often directly beneficial to plants. Direct experimental evidence that such is the case has not yet been furnished.

Alkali Soils.[3]—Alkali consists of soluble salts. When present in the soil in excessive quantities, these salts interfere with the growth of plants, or prevent their growth entirely.

The ordinary "alkali" salts are sulphate of soda, chloride of soda, and carbonate of soda. The salts first named, when crystallized in the surface of the soil, appear as white substances, and generally form what is known as *white alkali.* Carbonate of soda has a corrosive action upon vegetable matter (usually found in the soil) producing a black solution or substance, and for this reason is called *black alkali.*[4] Carbonate of soda is especially injurious, for it causes the soil to become hard so that water will not easily penetrate it. It is also more injurious to plants than the less corrosive alkali salts.

[1] See, however, Arendt, Jahresber, Agr. Chem., 1858, p. 125.

[2] Withers and Fraps, Report North Carolina Exp. Sta., 1902-3, p. 53.

[3] Alkali Soils of the United States, Bulletin 35, Bureau of Soils.

[4] California Bulletin 128.

Other salts than those mentioned above may be present in alkali. Calcium chloride, for example, may give the soil a black color, and have the appearance of black alkali, but it is not as injurious as carbonate of soda. Nitrate of soda has been found in Colorado soils.[1]

Origin of Alkali.—Alkali comes originally from the decompo-

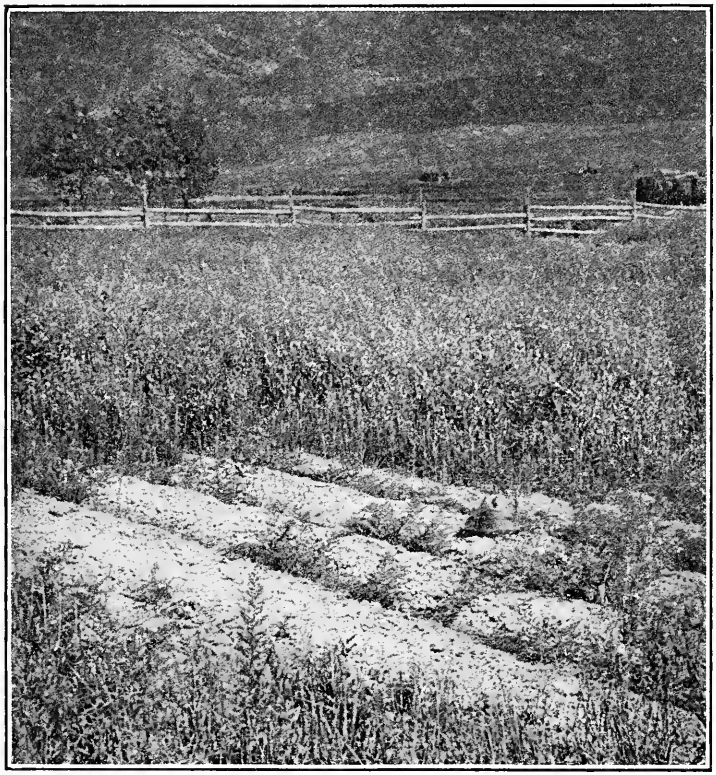


Fig. 63.—Alkali spot remaining in reclaimed field, Utah. Bureau of Soils.

sition of rocks. In climates where there is an abundance of rain, and much water passes through the soil, the alkali salts are

[1] Headden, Bulletin 178, Colorado Station.

washed out about as fast as they are formed and carried into streams, and thence to the sea.

In arid climates, since the rainfall is not sufficient to wash out the soluble salts, they accumulate. As long as these salts are distributed uniformly through the mass of the soil, they cause no

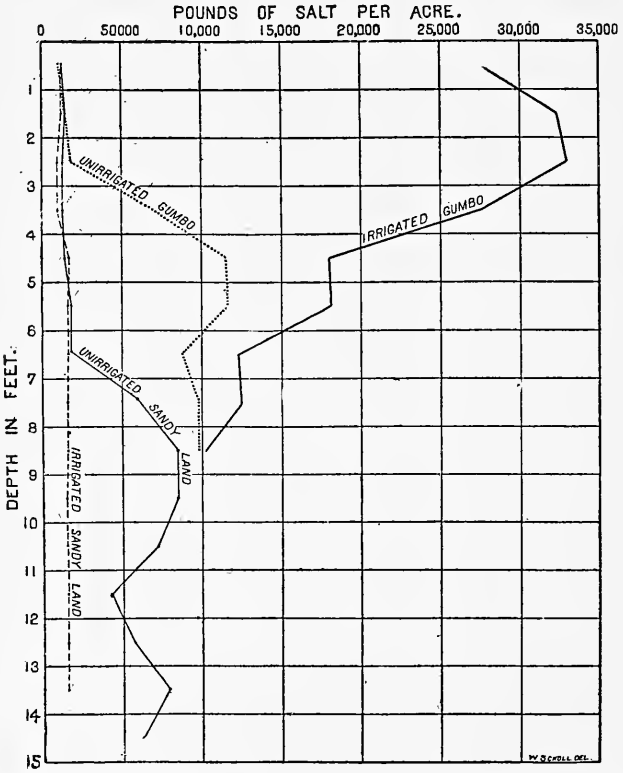


Fig. 64.—Salt content of sandy land and of gumbo soil, before and after irrigation. Irrigation causes the alkali to rise to near the surface of the gumbo soil. Bureau of Soils.

injury, but the alkali may accumulate in the surface-foot of the soil, or it may be carried away to accumulate in another field.

When water comes in contact with the soil, it dissolves the soluble constituents as far as it penetrates. If afterwards it

rises and evaporates, it leaves there all the alkali which it held in solution. Thus the alkali originally distributed through the soil may be concentrated near the surface, thereby causing injury to plants. Checking evaporation by cultivation, mulching or shading the land by crops, will check the rise of alkali. It sometimes happens that the alkali is concentrated in the eleventh or twelfth foot of the soil. Under moderate irrigation, the water will not penetrate to this depth, but excessive irrigation will carry water to such depths as to dissolve the alkali in the depths of the soil, and evaporation may then bring it near the surface, so as to cause injury. Soils have the power of elevating water to some distance, through the small spaces between the particles.

Irrigation waters, so necessary in arid regions, always contain dissolved salts. These are left behind when the water evaporates. If the water is of poor quality, only a few applications may be sufficient to charge the soil with alkali. Even a good irrigation water may give rise to alkali if all the salts it contains are allowed to accumulate in the soil.

Excessive irrigation, without under-drainage, gives rise to alkali.[1] This is evident first in the low-lying lands. The excess of water flows off into them, and raises the level at which the water saturates the soil (known as the water table), until in some cases, the water comes to the surface. The alkali is washed from the higher ground, and the water evaporates in these low places, leaving the alkali near the surface. The land is thus converted into alkali flats. Even where the water does not come to the surface, whenever it comes within such a distance of the surface that the capillary action of the soil grains has the power to bring it to the evaporating point, alkali will accumulate. The constant rise of the water containing salts and the evaporation of the water, leaving the salts behind, will accumulate alkali even if the water in the soil does not contain much alkali. Usually, however, such water contains some alkali.

Alkali will accumulate at any point where the water constantly evaporates, as on the sides of irrigation canals.

[1] Dorsey, Bulletin 34, Bureau of Soils.

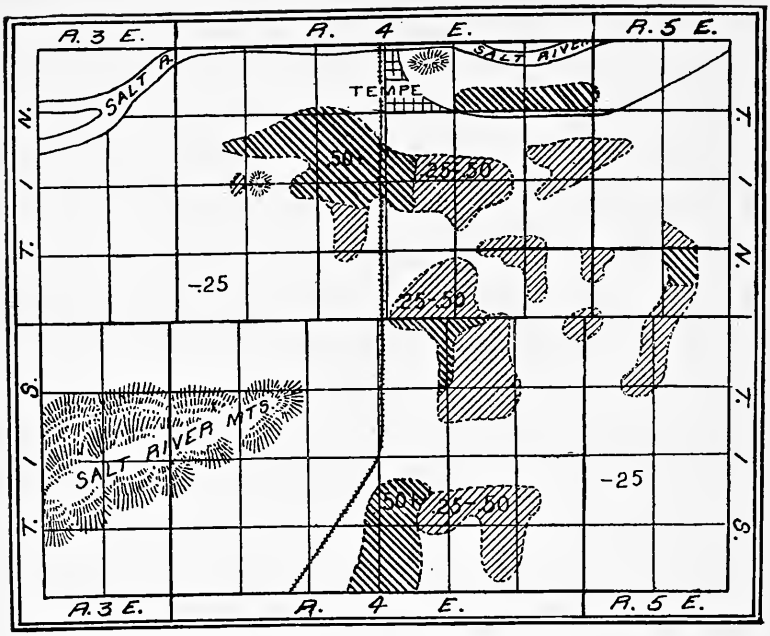


Fig. 65.—Distribution of alkali in soils near Tempe, Arizona—less than 25 per cent., 25 to 50 per cent. and over 50 per cent.

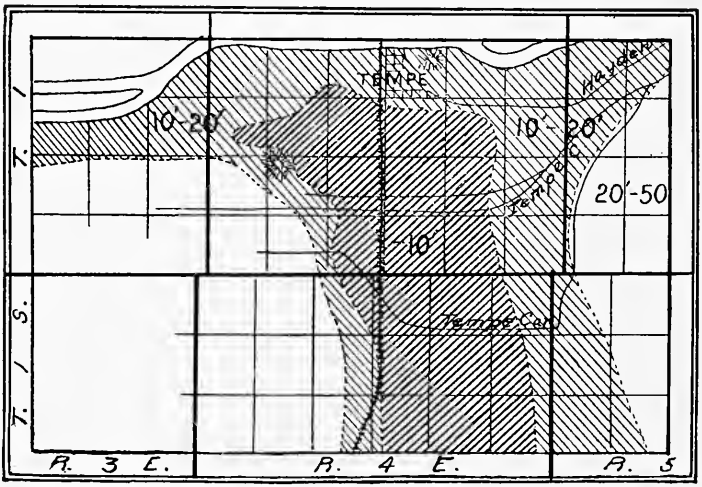


Fig. 66.—Distance to standing water in soils near Tempe, Arizona—less than 10 feet, 10 to 20, 20 to 50 feet. Compare Fig. 65. Bureau of Soils.

Whenever the water table rises, in land under irrigation in arid sections, to within four or five feet of the surface, it is a sign of danger. Such a rise means that the water in the soil is in such a distance of the surface that the salts will be constantly moving from the reservoir in the soil water, and accumulating in the soil. Injury will result if such an action continues. The remedy is drainage.

The bulk of the alkali salts in an arid region will be usually found some distance from the surface of the soil, when the water table is many feet below the surface. The depth at which this accumulation occurs depends to some extent upon the depth to which the rainfall penetrates. For example, Thomas H. Means found that the alkali salts in coarse sands of a certain district were largely four to eight feet from the surface, while in sandy loam, in which the rain can not penetrate so deeply, the alkali occurs at a depth of three or four feet. The rain dissolves the alkali and carries it down into the soil. On evaporation, some of the alkali returns to the surface, but the bulk of the evaporation must take place below the surface, for otherwise the alkali which is washed down would be brought up again.

Surface accumulations of alkali salts take place where the ground-water is sufficiently near the surface to cause the bulk of the evaporation of water to take place at or near the surface. Dissolved material from the soil, and that brought in by the ground-water, will be brought to the surface. Hence basin-like depressions surrounded by sloping land usually contain alkali.

Effect of Alkali on Plants.—Alkali[1] usually causes injury at the base of the trunk, or the root crown of the plant. The bark of green herbaceous stems is usually turned to a brownish color for half an inch or more, and is soft and easily peeled off. The rough bark of trees is turned nearly black, and the green layer turns brown. The plant either dies, or becomes unprofitable to the grower.

The amount of alkali which various plants will stand depends upon a number of conditions, among which are the age of the

[1] California Bulletin 128, p. 5.

plant, the character of the soil, the composition of the alkali, the distribution of the alkali, and other conditions which influence the growth of the plants themselves. The most injurious salts are the carbonates; the least injurious are the sulphates.

The California Experiment Station[1] has endeavored to determine the tolerance of various plants for alkali by estimating the amount of alkali in soils in which the respective plants did well or ill. The depth of four feet was chosen, because the strata below that depth contain little alkali, and because rainfall or irrigation water ordinarily does not penetrate below that depth. The total amount in this depth must be considered.

The results of these California investigations are as follows. These figures, as stated, are tentative and subject to change:

HIGHEST AMOUNT OF ALKALI IN WHICH PLANTS WERE FOUND UNAFFECTED, IN POUNDS PER ACRE TO THE DEPTH OF FOUR FEET.

	Sulphate (sodium sulphate)	Carbonate (sodium carbonate)	Chloride (sodium chloride)	Total salts
Grapes	40,800	7,550	9,600	45,800
Olives	30,640	2,880	6,640	40,160
Figs	24,480	1,120	800	26,400
Almonds	22,720	1,440	2,400	26,560
Oranges	18,600	3,840	3,360	21,840
Pears	17,800	1,760	1,360	20,920
Apples	14,240	640	1,240	16,120
Peaches	9,600	680	1,000	11,280
Prunes	9,240	1,360	1,200	11,800
Apricots	8,640	470	960	10,080
Lemons	4,480	480	800	5,760
Mulberry	3,360	160	800	5,760
Salt bush	125,640	18,560	12,520	156,720
Alfalfa (old)	102,480	2,760	5,760	110,320
Alfalfa (young)	11,120	2,360	760	13,120
Sorghum	61,840	9,840	9,680	81,360
Sugar beet	52,640	4,000	5,440	59,840
Sunflower	52,640	1,760	5,440	59,840
Radish	51,880	8,720	2,240	62,840
Wheat	15,120	1,480	1,160	17,280
Burr clover	5,700	11,300	—	17,000
Hairy vetch	63,720	2,160	3,160	63,360

[1] Loughridge, Bulletin 133.

The Bureau of Soils[1] of the United States Department of Agriculture divides soils into six grades, according to their average content of soluble salts to a depth of six feet.

	Percentage of total salts in soil	Black alkali per cent.	Crop behavior
Grade 1....	0.0-0.20	Less than 0.05	Common crops not injured unless salt is concentrated in first foot.
Grade 2....	0.20-0.40	0.05-0.10	All crops will grow except those most sensitive, but at the higher limit all except those that are truly resistant are distressed. Alfalfa grows but hard to get a good stand. Sugar cane, sorghum and barley do well.
Grade 3....	0.40-0-60	0.10-0.20	Not suitable for common crops. Usually devoted to pasture.
Grade 4....	0.60.1.0	0.20-0.30	Almost worthless for farming or fruit growing.
Grade 5....	1.0-3.0	Over 0.30	Worthless.
Grade 6....	Over 3.0		Worthless.

The quantities of alkali mentioned above refer to the total quantity of soluble salts.

Utilization of Alkali Soils.[2]—(1) *Growth of Resistant Crops.*—One method of utilizing alkali soils is to grow crops which will resist the action of the alkali present. One of the most resistant crops is salt bush, which endures drouth as well as alkali, and is used for pasturage, or as a hay crop. Sorghum, oats, and sugar beets have a high resistance for alkali, also some varieties of barley, but it is difficult to secure a stand of these crops when more than 0.6 per cent. of the total salts is present.

(2) *Treatment of Black Alkali.*—Black alkali, due to sodium carbonate, may be converted into sodium sulphate by means of gypsum. The sulphate is much less harmful to plants and the

[1] Dorsey, Bulletin 35, p. 24.

[2] Hilgard, Bulletin 128, California Exp. Sta.

A

B

Fig. 67.—Orange grove, (A) suffering from alkali, (B) after the alkali has been driven down by irrigation. California Station.

tilth of the land is decidedly improved. If much alkali is present, gypsum alone will not be sufficient because it does not remove the alkali, but merely changes it to another form. No chemical treatment is known which will counteract the effects of white alkali.

(3) *Scraping the Surface.*—At the end of a dry season, when the alkali has risen to the surface, it may be scraped off and carted away. This method might be used for small spots.

(4) *Flushing the Surface.*—This method consists in flooding the land with water and drawing it off after a short time. This method can not be used for any soil in which the water sinks in rapidly, because the water will carry the alkali with it into the soil. With rather heavy, impervious soils, with the alkali largely at the surface, the method may prove successful.

(5) *Flooding Without Drainage.*—For this method, the soil must be naturally well under-drained, with the water table several feet below the surface. The water used in flooding must go through the soil, and into the drainage. The method employed is to level the field, and cover the soil with water to the depth of several inches, the water being held on the soil by means of dikes or levees so that it soaks into the soil. Repeated flooding will carry the alkali out in the drainage waters. As already pointed out, this method can only be applied to soils which are naturally well under-drained, and on which the flooding will not raise the level of the water-table to a dangerous extent.

(6) *Flooding and Drainage.*[1]—Flooding together with artificial drainage will reclaim any alkali land; provided, of course, that the flooding is carried out often enough, and with sufficient water, and provided that the drainage is sufficient. Drainage is largely a matter of engineering. The drains should be at least three feet deep; on some soils four or five feet is better. In heavy soils they should be from 25 to 100 to 150 feet apart; in sandy soils intervals of 250 to 300 feet may answer the purpose.

Prevention of Alkali.—Accumulation of an excess near the surface is most to be feared. If the alkali is below the root zone of the plants it can do no damage. Plants may grow and do well

[1] Bulletin 34, Bureau of Soils, also Bulletin 44.

with their roots just above an accumulation of alkali, but if the alkali rises to the roots, or if deeper rooting crops are grown, injury will result.

In order to prevent the rise and accumulation of alkali, the irrigator must keep the main movement of the water downward through the soil and out in the ground-water. If the water movement is maintained in this direction, the alkali will not accumulate in the soil. The movement need not be at all times in this direction, but the main movement must be this way, or alkali will accumulate.

If the main movement of the water is up through the soil, alkali will accumulate. In a sub-irrigated soil, the movement of water is up, due to evaporation of water, and to transpiration from the leaves of plants. Hence, sub-irrigation means an accumulation of alkali.

Furrow-irrigation is a kind of sub-irrigation. The soil at the top of the furrow is irrigated from below, and, in this particular part of the soil, the movement of the water and dissolved salts is up, so that it will accumulate alkali. If furrow-irrigation is used in places liable to alkali, the soil should occasionally be leveled and flooded—sufficiently often to keep the main movement of the water down through the soil.

If flooding is practiced, and hillocks occur which are not covered by the water, such spots are sub-irrigated, and alkali will accumulate in them. Within these hillocks, the movement of water is upwards, due to evaporation from the surface. Such hillocks should be leveled before flooding begins.

Anything which will counteract surface evaporation will aid in keeping the main movement of the water down and through the soil. The greater the extent that evaporation is prevented, the less water is needed for the irrigation. Evaporation from the surface, therefore, should be prevented as much as possible. Careful and frequent cultivation will produce a mulch which will do much towards checking evaporation. Trees or crops on the land will also shade the surface and check evaporation.

If the water-table is too near the surface, flooding must be

more frequent or the land must be under-drained. Too frequent flooding may keep the ground too wet, so that under-drainage is really the practical remedy. Whenever the water-table is at such a distance that the capillary action of the soil can bring water from it to the surface, there is great danger of alkali. In such a soil, the rise of water from the ground water is continuous, so that more must be used in irrigation to cause the main movement of the water to be downwards. By lowering the water-table by means of drainage, the water-table may be brought below the power of the soil to elevate it, thus checking the movement of water, and the alkali with it, towards the surface. The right depth for the water table depends upon the character of the soil. In coarse sand, water may be raised over five feet. It appears possible that in fine sand, so often found in alkali districts, water may be raised as much as twelve to fifteen feet.

How much flooding will keep the main movement of the water downward and through the soil will depend, therefore, upon the water-table and the character of the soil, and the thoroughness of the cultivation. The composition of the ground-water, and the composition of the irrigation-water are important factors to consider.

The alkali question is, in many localities, largely a question of proper drainage.

Quantity of Irrigation Water.—The quality of the irrigation water which can be used upon soils without injury depends upon the kind of soil, the character of the under-drainage, the rainfall of the area, and the manner in which the water is used. If the soil is easily penetrated by water, and well drained, water of comparatively high mineral content may be used, provided that it is used in such a manner as to keep the main movement of the water through the soil and into the drainage. In humid regions, a water containing more salts may be used than in arid regions, since less water is used and the natural rainfall will aid in washing the alkali out of the soils. With a heavy clay soil, however, and especially if alkali carbonates are contained in the water, there is always danger.

The limit of concentration of irrigation water has been placed by some authorities at 2,000 or 3,000 parts per million. With these concentrations, however, injury will result if the alkali is allowed to accumulate, and is not washed from the soil. Even comparatively small amounts of mineral matter may give rise to alkali in time, if the soluble salts are allowed to accumulate.

Thomas H. Means[1] found water containing as much as 8,000 parts per million of soluble salts used in the Desert of Sahara, many of the crops grown being quite sensitive to alkali. The Arab gardens are divided into plots about twenty-feet square, with drainage ditches about three feet deep between them. A large quantity of water is applied at least once a week; more often, water is applied twice, the check method of irrigation being used. Thus a continuous downward movement of water is maintained, and, since the soils are light and sandy, they are well drained, and there is little opportunity for the soil water to become more concentrated than the water applied.

It is evident that the more salts contained in the water, the better should be the under-drainage, and the more freely the water should be used. On clay soils, the matter is more difficult. Alkali is so hard to remove from some of these soils, even if under-drained, that it is doubtful if any except water of high purity should be used on such soils.

[1] Circular No. 10, Bureau of Soils.

CHAPTER XIII.

LOSSES AND GAINS BY THE SOIL.

Under natural conditions, a large portion of the material taken from the soil by plants returns to it again. The plant dies and decays. Droppings from animals which have eaten plants are distributed on the soil. Nevertheless there is some loss of material due to leaching. We have seen that in the weathering of rocks into soils, large percentages of material are removed, but this process has taken long periods of time. Soils which are highly weathered contain much less plant food than those less weathered; this shows that losses by percolation occur under natural conditions. Under cultivation, there may be much greater losses, due to the smaller amount of vegetation on the soil at certain seasons, and to the removal of the crops.

Gain by Rainfall.—In Chapter III we saw that the rain dissolves and brings down small amounts of ammonia, nitrates, dust, and other substances. The quantity of the most important constituent, nitrogen, brought down by the rain, has been shown to average about 8.0 pounds per acre. (Chapter III.)

Loss in Percolation.—Of the water which falls on the soil, a portion runs off, a portion evaporates or is transpired by plants, and a portion penetrates through the soil, and either reappears in springs, drains, wells, or seepage water, or else sinks deep into the earth. This is the *percolating water.* The water which percolates dissolves some of the material that comes in contact with it, thereby causing a loss of material. The water contains silica, organic matter, potash, soda, lime, and magnesia, in the form of carbonates, sulphates, phosphates, chlorides, and nitrates. The more important of these constituents, from an agricultural point of view, are the potash, phosphoric acid, nitrogen, and lime.

The amount of loss by percolation depends upon a number of factors:

(1) *The Quantity of Percolating Water.*—This depends upon the amount of rainfall, whether the land is bare or covered with vegetation, the character of the soil, etc. Unless the rainfall is

sufficient to saturate the soil, and pass into the ground water, there is no percolation. Plants, by withdrawing water from the soil and causing it to evaporate, diminish the quantity which percolates. As more of the rainfall will penetrate an open, porous soil than a compact soil, there would be a greater surface off-flow from the latter. Soils which retain water near the surface suffer greater losses by evaporation. See Chapter VII.

(2) *The Composition of the Soil Extract.*—This depends upon the fixing power of the soil and the solubility of its constituents. It also depends on the kind and quantity of the various additions made to the soil. The application of fertilizers almost always increases the quantity of potash and nitrogen in the soil extract and consequently increases the loss of plant food. Ammonium sulphate and potash salts also increase the quantity of lime in the soil extract.

(3) *The Presence or Absence of Vegetation.*—Besides affecting the amount of percolation, vegetation withdraws plant food from solution and thereby diminishes the loss in percolating water.

Study of the Loss.—The loss by percolation may be studied in two ways, both of which have their limitations:

(1) By determination of the amount and composition of the percolating water. For the purposes of this experiment, a section of the soil must be enclosed in a water-tight receptable, so arranged that all the water which percolates may be collected, measured, and subjected to analysis.

A section of soil in its natural condition, may be isolated by trenches, enclosed by brick walls, and then separated from the subsoil, so that the percolating water may be collected in a suitable vessel. This was the method used in preparing the drain-gauges (as they are called) at Rothamsted. See Chapter VII.

Soil may also be placed in boxes of cement[1] or cans of galvanized iron, or other material, arranged with suitable tubes and collecting vessels. In such case, the soil is stirred and aerated and is otherwise under unnatural conditions. The apparatus

[1] New York, Cornell Station Report, 1909.

should be left for sufficient time to allow readjustment to take place.

All the water which falls on the soil in such an apparatus must either percolate or evaporate. The percolation will therefore be in excess of that in a free area, where a portion of the water runs off.

(2) The second method[1] consists in determining the quantity and composition of the water from tile drains in the field. Tile drains run when the water does not pass into the subsoil rapidly enough to keep the soil from becoming saturated in the vicinity of the drains. The quantity of drain water does not, therefore, represent the quantity of water which percolates, but its composition should represent to a certain extent the composition of the percolating waters.

Quantity of Loss by Percolation.—The composition of the drainage water from some of the plots at Rothamsted[2] is given in the following table:

ANALYSIS OF DRAINAGE WATERS IN PARTS PER MILLION.

Rothamsted	Phosphoric acid	Potash	Nitric nitrogen	Lime
Unmanured wheat plot	0.63	1.7	3.9	98.1
Ammonium salts only	1.44	1.9	13.9	154.1
Ammonium salts and super-phosphates	1.66	1.0	15.3	165.6
Full mineral dressing and ammonia	0 91	2.9	14.0	181.4
Farmyard manure	—	3.4	16.1	147.4

If we assume a downward percolation of 10 inches of drainage water, 1 part per million of water corresponds, in round numbers, to 2¼ pounds per acre per annum. According to this estimate, from 1½ to 3¾ pounds phosphoric acid, 2½ to 12½ pounds potash, and 9 to 36 pounds nitrogen are lost in the drainage waters a year, according to the condition of the soil.

At Rothamsted, the average amount of nitrogen contained in the crops (wheat) in 30 years on the unmanured plots was 18.6 and 20.3 pounds; the estimated loss by drainage from tiles, 10.3 and

[1] Jour. Agr. Sci., 1906, p. 377.

[2] Hall, An Account of the Rothamsted Experiments, p. 237.

12.0 pounds respectively, with an estimated gain of 5.0 pounds nitrogen derived from rain and dew. From 2/9 to ¼ of the total loss of nitrogen passes into the drainage waters.

Gains by Material Dissolved in Capillary Water.—A certain portion of the water which sinks into the subsoil, rises again to be evaporated near the surface or transpired by plants. It has been claimed that this water may bring dissolved material to the surface soil. Such is indeed the case in arid regions where soluble salts are within reach of the water. The alkali zone may rise or sink to some extent with the dry or wet character of the season. In humid sections, however, material is dissolved by the water as it passes through the surface soil, and the gain can be due only to a longer contact with the subsoil. There may be some gain of this kind, but it would have to be considerable to counterbalance the material dissolved in soil water which enters the ground water and does not return to the surface. The writer has been able to find no experimental data showing the relative solubility of the material of soils and subsoils, and the relative quantity of water which reaches the subsoil and which returns to the surface.

Losses by Washing.—Water running off on the surface carries soil particles with it, so that as a general rule the surface soil is deeper in valleys and thinner on hill-sides. The particles are carried to some extent in the water of streams, and may be deposited elsewhere along the course of the stream, or carried to the sea. In regions of heavy rapid rains, the running water may cut ravines and gullies, and practically destroy unprotected hillside land. Vegetation is a protection against such loss, and so is anything which checks the rapidity of the flow of the water. Proper hillside terracing is the best treatment for cultivated land.

Loss by Bacterial Action.—The losses by bacterial action fall on the organic matter and the nitrogen of the soil, none of the other materials being directly lost in this way. Excessive nitrification is followed by losses of nitrogen as nitrates in the drainage water, usually as calcium nitrate, which involves a loss of lime, also. Nitrogen is also lost to the soil by denitrification, par-

ticularly when the soil is water-logged or receives excessive quantities of manure. Considerable losses of nitrogen take place in cultivated soils.

Organic matter is lost from all cultivated soils by oxidation. The factors which influence the oxidation of organic matter have been discussed in a previous chapter.

Gains of Nitrogen by Bacterial Action.—Considerable amounts of nitrogen may be assimilated by legumes in connection with bacteria. Crimson clover, according to the New Jersey Station, may take up 200 pounds nitrogen per acre per year. Similar studies at the Delaware Station[1] with various legumes showed the yields to range from 31 to 140 pounds nitrogen per acre. Velvet beans gained 213 pounds per acre in Alabama experiments, 172 pounds in Louisiana, and 141 pounds nitrogen in Florida. Cowpeas gained 70 pounds in Alabama,[2] and 35 per cent. was left in leaves and stubble if the vines were mowed. Like results with other legumes showed an average gain of 122 pounds nitrogen per acre for sixteen States.

It is believed by some that appreciable quantities of free nitrogen may be fixed by soil bacteria, which have no connection with legumes, especially when the soil receives manure or other vegetable matter for the bacteria to feed upon. This subject requires further investigation. Bacteria which have this power are certainly present in the soil, but to what extent they aid in maintaining the supply of combined nitrogen in the soil, is not known.

Losses in Cropping.—This is due to the removal of plant food in that portion of the crop which is taken from the land. The amount lost in this way varies largely, depending on (*a*) the size of the crop, (*b*) the kind of crop, (*c*) the portion of the crop removed, and (*d*) the treatment of the residual portion, besides the various factors which influence the amount of plant food taken from the soil by the crop.

The fact that the amount of plant food removed depends

[1] Bulletin No. 60.

[2] Bulletin No. 120.

largely on the size of the crop, requires little discussion. The plant food removed varies largely with the kind of crop. The following figures show the relative amounts of plant food removed by a portion of different crops. These figures are from average values; indivdual analyses may vary somewhat.

The quantity of plant food removed by the marketed portion of various crops of the size named,[1] is as follows:

POUNDS OF PLANT FOOD.

	Phosphoric acid	Nitrogen	Potash
Corn, 40 bushels (corn and cob)	19.0	38.0	13.0
Wheat, 25 bushels	13.0	29.0	9.0
Oats, 40 bushels	10.0	25.0	7.0
Cotton lint (250 pounds)	0.1	0.8	0.7
Potatoes, Irish, 100 bushels	10.0	20.0	36.0
Potatoes, sweet, 200 bushels	20.0	28.0	72.0
Alfalfa, 4 tons	50.0	183.0[2]	143.0
Sugar cane, 20 tons	15.0	153.0	44.0
Onions, 30,000 pounds	37.0	72.0	72.0
Rice, 1,900 pounds	12.0	23.0	5.0

Loss in By-Products.—The by-products consist of the straw, chaff, cottonseed, etc., and the loss of plant food depends upon how they are disposed of. If they are removed, and sold, or otherwise taken away, all the plant food in them is lost. If burned and the ashes returned to the soil, the nitrogen is lost. If turned under, the loss is much less. If made into manure, which is afterwards placed in the soil, there is still some loss.

PLANT FOOD IN BY-PRODUCTS OF THE CROPS IN PRECEDING TABLE.

	Phosphoric acid	Nitrogen	Potash
Cotton seed (500 pounds)	7	16	8
Cotton stalk and leaves	12	32	23
Corn stalk and leaves	6	22	29
Wheat straw	5	13	14
Oat straw	4	10	21
Rice straw	3	14	37

[1] Bulletin No. 125, Texas Station.

[2] A portion of this nitrogen comes from the air.

Loss of Various Cropping Systems.—When a soil is continuously cultivated to the same crop, such as wheat, and all the material removed, it decreases in productiveness, until it reaches a low crop level, at which production may be maintained for a number of years.

If the soil receives fertilizers or manure continuously, the losses of plant food will be greater, and the soil will adjust itself to a higher level of productiveness as long as conditions are so maintained.

Distribution of the Losses of Nitrogen.—At Rothamsted, study was made of the disposition of the nitrogen added to the soil during a period of 50 years. Analyses were made of soil from different plots treated differently, at the beginning and end of the period, of the crops, and of the water from tile drains. Of 86 pounds nitrogen added per acre per year in 50 years, the disposition seemed to be as follows:

DISPOSITION OF NITROGEN, PER YEAR.[1]

	Average	Maximum	Minimum
Removed in crops, 50 years	16.7	25.0	8.0
Accumulated in soil	7.6	12.5	3.0
Loss from tile drains	26.7	31.0	19.0
Other losses	35.0	44.0	26.0

The maximum loss took place with ammonium salts alone. The amount of the total loss was estimated by adding the amount of nitrogen in the soil at the beginning to the total amount added as a fertilizer and subtracting from this the amount present in the soil at the end of the fifty years. The nitrogen lost may have passed into the ground water below the drains. In this work, only 17 per cent. of the nitrogen was used by the crop. It is quite possible that with smaller applications of nitrogen, much smaller losses and much better utilization of the nitrogen, would have taken place. The excessive amounts of nitrogen used caused heavy losses.

[1] Bulletin 106, Office Exp. Sta., U. S. Dept. Agr.

Gains of Organic Matter.—The soil gains organic matter through residues of crops, weeds, green crops, and manure. Crops are divided into two classes with reference to their effect upon the organic matter of the soil—namely humus-decreasing and humus-increasing. Those crops which leave enough, or more than enough vegetable matter in their roots and stubble to restore the loss which takes place during their growth, are called *humus-increasing* crops. They are generally crops which receive little or no cultivation, and which leave large amounts of roots and stubble. Crops such as clover and grasses are humus-increasing.

Those crops which do not leave enough organic matter to replace the loss by oxidation during their growth are called *humus-decreasing*. On account of the cultivation which these crops receive, there is a greater loss of organic matter than with the first group mentioned, and less organic matter is contained in the stubble. Cotton, corn, potatoes, and beets belong to this group.

There are some crops which belong to the one or the other of these groups according to the disposition made of the residues therefrom. For example, if rice straw is removed or burned, it is a humus-consuming crop, while if the straw is plowed under there may be little or no loss of humus.

The quantity of organic matter lost when humus-consuming crops are grown also depends upon the disposition of the residues. Any treatment which results in loss of organic matter that might be plowed under, such as burning off of corn stalks or grass, etc., increases the loss of organic matter from the soil, and vice versa.

Green crops, when plowed under, increase the organic matter of the soil. Their chief use is to secure nitrogen from the air. Plowed under very green, they decompose rapidly and may sour the soil. If allowed to mature, decomposition takes place much more slowly. Manure is one of the best means of maintaining the organic matter of the soil, but many farms do not make enough manure to suffice for this purpose.

Formation of Humus.—The accumulation of humus takes place more largely under conditions of reduction than conditions of oxidation. Climate, weather, nature of soil, etc., are all of in-

fluence. A high temperature is favorable to decay only when accompanied by sufficient moisture, but, as a general rule, a low temperature is favorable to accumulation of humus. The less the permeability of the soil, the slower is the oxidation and the greater is the accumulation of humus. The greater the quantity of plant substance produced, the larger the accumulation of organic matter in the soil. Dry plant residues decay more slowly than green, the straws of cereals more rapidly than the leaves of trees. Wood decays more slowly than any of the other materials named.

In cultivated soil, in spite of the addition of manure, the accumulation of humus is less than in similar uncultivated soils covered with perennial crops, such as pastures, forests, etc. Both lose organic matter, but the protective covering of the latter decreases the loss or even causes an increase. The following table shows the carbon content of the soil under three forms of treatment:

GRAMS. OF CARBON PER 1,000 GRAMS. SOIL.

	Corn	Potatoes and barley	Sanfoin
At the beginning	15.2	16.2	12.9
After growing 4 years	7.6	7.1	13.3
Loss	7.6	9.1	—
Gain	—	—	0.4

A loss of over half the organic carbon in the soil occurred with the cultivated crops, while with the uncultivated crop (sanfoin) there was a slight gain. Manure was added to the cultivated plots.

It appears that cultivated soils become poorer in carbon, no matter how much manure is applied, and this impoverishment ceases and the soil begins to get richer when the land is filled with perennial plants.

CHAPTER XIV.

MANURE.

Manure consists of the excrements of domestic animals, mixed with more or less bedding or litter. Barn-yard manure is the ordinary mixture of animal excrements, litter, etc., which are accumulated on the farm.

Composition of Manure.—Manure is very variable in composition, depending on the kind and age of the animal, the kind and amount of food, the litter or absorbents used, and the method of keeping or preserving it. Ordinary barn-yard manure which has received reasonable care, may be safely assumed to vary in composition between the following limits:

	Per cent.	Average per cent.
Nitrogen	0.4-0.8	0.47
Phosphoric acid	0.2-0.5	0.33
Potash	0.4-0.8	0.49
Water	0.60-0.75	67.6

The average composition of carefully preserved manure from different animals is about as follows:[1]

PERCENTAGE COMPOSITION OF MANURE.

	Water	Nitrogen	Phosphoric acid	Potash
Sheep	59.5	0.77	0.39	0.59
Calves	77.7	0.50	0.17	0.53
Hogs	74.1	0.84	0.39	0.32
Cows	75.3	0.43	0.29	0.29
Horses	48.7	0.49	0.26	0.48
Hens	56.0	0.7-2.0	0.5-2.0	0.25-0.9

Comparative Value of Solid and Liquid Manure.—The solid manure of animals consists of the undigested residues of the food. The urine contains the fertility ingredients which have been digested. The composition of the solid and liquid excrement

[1] Beal, Farmers Bulletin No. 77.

from farm animals is approximately as follows, though considerable variations occur:

PERCENTAGE COMPOSITION OF EXCREMENTS.

	Water		Nitrogen		Phosphoric acid		Potash	
	Solid	Liquid	Solid	Liquid	Solid	Liquid	Solid	Liquid
Horses	76	89.0	0.5	1.2	0.4	trace	0.4	1.3
Cows	84	92.0	0.3	0.8	0.3	trace	0.1	1.3
Swine	80	97.5	0.6	0.3	0.5	0.13	0.4	0.45
Sheep	58	86.5	0.8	1.4	0.6	0.05	0.45	2.0

Poultry excrement, when fresh, contains about 1 per cent. nitrogen, 0.8 per cent. phosphoric acid, and 0.4 per cent. potash. The results of an experiment made at the Pennsylvania Experiment Station, to ascertain the distribution of the fertilizing ingredients among the solid manure, the liquid manure, and the milk or increase in weight, are as follows:

	Liquid manure	Solid manure	Milk or increase
	Per cent.	Per cent.	Per cent.
Nitrogen	50	33	17
Phosphoric acid	trace	75	25
Potash	75	16	9

Loss of urine therefore involves the loss of 50 per cent. of the nitrogen fed, and about 75 per cent. of the potash.

Influence of Age and Kind of Animal.—An animal which is not gaining flesh, producing milk, or laying eggs, etc., will excrete practically all the potash, phosphoric acid, and nitrogen eaten. These ingredients are taken in with the food, used, and are excreted in the waste products. If no flesh, etc., is produced, the outgo and income must be equal. A young growing animal retains in the bones, flesh, etc., a portion of the fertilizing materials fed to it. Animals producing milk, laying eggs, etc., utilize some of the phosphoric acid, and nitrogen in these products.

The Mississippi Experiment Station determined income and outgo of plant food, and found that young fattening steers excrete on an average 84 per cent. of the nitrogen, 92 per cent. of the potash, and 86 per cent. of the phosphoric acid of the food consumed.

Differences in the composition of manure from different animals are due in part to difference in the food eaten by the animal, and in part to the water-content of the manure. Animals, such as hogs, which feed on concentrated foods, produce a stronger manure than those which require more bulky food, such as horses and cows.

Sheep manure is a rich manure containing only a small amount of water. It ferments more rapidly than cow manure, but not as readily as horse manure. It is concentrated and valuable for gardening purposes.

Horse manure is dry, undergoes fermentation rapidly, and generates a high heat on account of its loose texture. In the process of fermentation the nitrogen is converted into ammonium carbonate, which, being volatile, is liable to be lost. A well fed horse at ordinary hard work will produce about 50 pounds of solid and liquid excrement per day.

Hog manure is very variable in composition. It contains much water, ferments slowly, and generates little heat in fermentation.

Cow manure is poorer than hog manure, decomposes slowly and generates little heat. A milch cow will excrete daily about 20 to 30 pounds liquid and 40 to 50 pounds solid excrement per day.

Poultry manure is rich in nitrogen. It ferments rapidly and easily loses nitrogen. In order to prevent loss from volatilization as ammonia, some preservative should be added to it.

Quality and Quantity of Feed.—Since manure can contain only the fertilizing constituents of the food, the composition of manure depends largely on the composition and amount of the food. If the food is poor in nitrogen, phosphoric acid, and potash, the manure will also be poor. The richest manure will be obtained when concentrated materials rich in nitrogen are fed, such as cottonseed meal, gluten meal, bran, clover hay, etc. Since

animals fed on heavy rations for fattening or for the production of milk must be fed concentrated food, it follows that manure is more valuable from these animals than from animals fed for maintenance. In many instances the value of the fertilizing materials contained in purchased feed is nearly as great as the food value. This is very often the case with cotton seed meal purchased in the Southern States. The farmer who saves both solid and liquid excrement in the manure, is getting two values for the money expended. If the liquid excrement is lost, something over 50 per cent. of the fertilizing value of the feed goes with it. The fertilizer constituents of the liquid manure are also more valuable, pound for pound, than those in the solid manure. The liquid manure contains in solution and readily available those substances which have been digested by the animal. The purchase of feeding stuffs accompanied by the careful saving of manure, is one way to secure plant food for the farm. This method is extensively applied in European countries.

Different feeding stuffs vary considerably in their content of plant food. The following table gives the manurial value of some farm products.

MANURIAL VALUE OF FARM PRODUCTS, POUNDS PER TON.

	Nitrogen	Phosphoric acid	Potash
Meadow hay	20.4	8.2	26.4
Clover hay	40.2	11.2	36.6
Potatoes	7.0	3.2	11.4
Wheat bran	49.2	54.6	28.6
Linseed meal	105.7	32.2	24.8
Cotton seed meal	135.7	56.2	29.2
Wheat	37.5	15.8	10.6
Oats	36.4	12.4	8.8
Corn	33.1	11.8	7.4
Barley	39.7	15.4	9.0
Milk	10.2	3.4	3.0
Cheese	90.6	23.0	5.0
Live cattle	53.2	37.2	3.0

Kind and Amount of Litter.—Litter is used to furnish a clean bed for the animal and to absorb the liquid excrement. It makes the manure easier to handle, increases its physical (and in some

cases, its chemical) action on the soil, and checks and controls decomposition. The materials used for litter are not, as a rule, rich in fertilizing ingredients. It is more important that all the fertilizing ingredients of the manure should be preserved than that its percentage composition should be increased or diminished.

Straw is usually used for litter because it is one of the by-products of the farm. It is a good absorbent, though rather poor in fertilizing constituents.

Leaves are good absorbents.

Dry peat is an excellent material, as it has a high absorbing power and contains fair amounts of nitrogen.

Sawdust is a good absorbing material, but poor in fertilizing constituents.

The composition of some materials used as litter is as follows:[1]

Pounds per Ton of Litter.

	Nitrogen	Phosphoric acid	Potash
Leaves	16	6	6
Straw	8–12	4–6	12–32
Peat moss	16	trace	trace
Sawdust	4–14	6	14
Spent tan bark	10–20		
Peat	20–40		

Losses of Manure.—All the plant food in the excreta of animals cannot be saved. There are some unavoidable losses in nearly all methods of collecting manure. The least loss of fertility occurs when the animals are fed in the field to be manured, as the excreta, solid and liquid—particularly the liquids—are then absorbed by the soil. When manure is stored or preserved, there is always a loss of plant food. The Rothamsted Experiment Station estimates that, as a rule, under English conditions, one-half of the nitrogen of the feed is lost, one-fourth of the phosphoric acid, and none of the potash. The chief causes of loss are (1) seepage, or penetration of the liquid manure into the soil; (2) weathering, or exposure to rain; (3) fermentation.

[1] Beal, Farmers Bulletin No. 77.

When the animals are stabled on a wood or dirt floor with insufficient bedding, a portion of the liquid excrement soaks into the ground. The quantity depends upon the tightness of the floor and the absorptive power of the manure or the litter. A similar loss occurs when the manure is stored in piles on the earth. A portion of the liquids sink in the earth. Cement floors prevent such losses, and are used to a considerable extent in certain localities. Clay when worked until puddled, and then tamped, makes a fairly good floor.

Loss by seepage may be decreased by using the proper quantity of litter, and by collecting and preserving the manure on an impervious floor. An excess of litter makes the manure too coarse. The following table[1] shows the absorptive power of various litters:

	Water retained by 100 pounds material after 24 hours
Wheat straw	220
Oak leaves (partly decomposed)	162
Sawdust	435
Peat	600
Peat moss	1,300
Soil rich in humus	50

The amount of litter should depend on the character of the food. Watery foods and those containing much nitrogen increase the secretion of urine and so increase the amount of litter necessary to absorb the urine and keep the animal clean. Manure protected from rain by a shed, according to Kinnard, produced 4 tons more per acre of potatoes, and 11 bushels more wheat, than the same quantity of manure not protected by a shed during the same period of time.

When manure is exposed to rain, a part of the fertilizing constituents is washed away, somewhat in proportion to the length of the exposure and the amount of rain. The soluble ingredients so lost are the more available and more valuable part of the manure. Experiments have been made in which a quantity of manure was weighed and subjected to analysis and after a certain

[1] Herbert, Exp. Sta. Record No. 5, p. 144.

period, again weighed and analyzed. The following are some of the results:

	Where made				
	New York	New Jersey[1]	New Jersey[1]	Canada	Ohio[2]
	Material				
	Horse manure	Cow dung	Dung and urine	Horse manure	Steer manure
Time (days)	180	109.0	109	365	90
Loss of nitrogen per cent	50%	37.6	51	33	28
Phosphoric acid	50%	51.9	51	16	14
Potash	50%	47.1	61	34	58

Exposure to rain certainly involves a considerable loss of fertility.

Fermentation.[3]—Two classes of bacteria take part in the fermentation of manure (1) Aerobic, which live only in the presence of oxygen, (2) Anaerobic, which live only when oxygen is excluded. On the outer surface of the heap, the aerobic bacteria are active, while the anaerobic ferments act in the interior of the heap where the supply of air is limited. The anaerobic bacteria are less vigorous in their action than the aerobic. They often produce foul smelling gases. The fermentation also varies according to circumstances. It depends on the temperature, the supply of air, the moisture, the composition of the material, and the preservatives used.

The optimum temperature for manure fermentation is about 131° F. The temperature may rise high enough to set the mass on fire, if it is dry enough. The temperature of the interior of the heap, where anaerobic fermentation is in progress, rarely rises over 95° F.

The supply of air is determined by the compactness of the heap.

[1] Bulletin 150.

[2] Bulletin 183.

[3] Herbert, Exp. Sta. Record 5, p. 146.

If the heap is too loosely built, the fermentation is too rapid, and large losses of nitrogen will occur.

Moisture, by lowering the temperature and excluding air, retards fermentation; loss of manure is decreased by keeping the manure properly moistened. Alternate wetting and drying is also bad.

Manure decreases rapidly in bulk during fermentation, the substances of which it is composed being decomposed partly into carbon dioxide and water. When the fermentation is not properly controlled, nitrogen may escape as free gas or as ammonia. The coarse materials are gradually decomposed and are to a considerable extent dissolved in the black liquid which oozes out of the manure heap. The mineral matter is also rendered more soluble.

The nitrogen in the liquid excrement is mostly present as urea or hippuric acid. These undergo fermentation rapidly, especially in a warm climate, producing ammonium carbonate, and considerable amounts of ammonia may escape into the air. Ammonia is produced in fermenting manure, and if the manure is allowed to dry out, or is too freely exposed to the air, considerable losses of ammonia take place.

Fermentation is controlled by keeping the manure heap compact and moist, and by the use of preservatives. Sprinkling the mass with water or liquid manure excludes air and prevents loss of ammonia. If the mass dries out, nitrogen is lost. Gypsum (land plaster), kainit, and acid phosphate are preservatives recommended to prevent loss of manure during fermentation, but it is doubtful whether they have any appreciable effect.

Methods of Saving Manure.—The following are some methods of saving manure:

(1) *Grignon Method.*—This method is used extensively in France. The manure is piled upon a stone or cement pavement in the farm courtyard, in flat, well packed layers. The liquid manure, and the drainage from the manure pile runs into a stone cistern. From time to time the liquid manure is pumped over the pile of solids. The object of this is to keep the manure moist

and to prevent loss by excessive fermentation, and also to cause the manure to decompose evenly. When thoroughly rotted, the

Fig. 68.—The Grignon system of keeping manure.

Fig. 69.—Liquid manure spreader. Switzerland.

manure is very dark, brittle mass, and is said to be very effective in its action.

(2) *Liquid Manure Method.*—This method is used in Germany, Belgium, and Holland. The liquid manure is carried to an underground tank by means of stone troughs. The solids are kept separate. The liquid manure is pumped out and applied to the soil about six times a year, or oftener.

(3) *Deep-Stall Method.*—The animals are kept in deep stalls with paved floors. Sufficient bedding is used to keep the animal dry and the manure is allowed to accumulate in the stall. The feeding rack and water vessels are hung on chains, so that they can be raised as the manure accumulates. The manure is taken out once or twice a year. When the climate is cool, this method has given good results. At the Pennsylvania Station,[1] there was a loss of only 5.7 per cent. of the nitrogen, 5.6 per cent. potash, and 8.5 per cent. potash, compared with 34.1 per cent. nitrogen, 19.9 per cent. potash, and 14.2 potash lost from similar manure in a covered shed.

(4) *Absorption Method.*—The liquids are absorbed with straw, peat, sawdust, or dirt, etc., and taken out with the solids. The manure is allowed to accumulate, or hauled out to the fields daily.

(5) *Feeding Off and Pasturing.*—When the crops are pastured or fed off, the manure is dropped directly in the field.

Application of Manure.—The kind and amount of manure to be applied depends on conditions. The least loss takes place when the manure is applied as fresh as possible. Manure decays more rapidly in an open soil than in a close soil (clay). If it is desired to improve the mechanical condition of a clay, fresh manure should be applied, but the fertilizing constituents act more rapidly in a clay soil when manure is well rotted. Fermenting manure seriously injures the quality of tobacco, sugar beets, and potatoes.

The manure may be (*a*) placed in heaps, and then spread, (*b*) spread broadcast and ploughed in, (*c*) applied in hill or drill with seed. The first method is objectionable, as the small heaps may lose fertility rapidly, and the spots made much richer than the remainder of the field. The second method is good if the manure

[1] Bulletin 63.

is soon ploughed in. The third method is applicable to some truck crops.

The amount of manure applied varies from 3 to 40 tons per acre. In arid or dry climates, the manure should be composted, and well rotted. Coarse manure should not be plowed under in the spring in dry sections, as the layer of manure will break the connection between plowed and unplowed soil, and cause the plowed soil to dry out more rapidly, thereby losing water needed for the crops. Coarse manure may be applied best as a top dressing on pasture land.

Well rotted manure may cause wheat to lodge. It can be applied to corn.

Practice in applying manure varies. In some places, heavy applications are made every four years or more. In other places, it is applied annually in smaller quantities. It is probably better to apply the manure once in a rotation of crops to the crop which does best with it. Manure is valuable not only for the plant food which it contains, but also for its physical and chemical effects on the soil. The lasting effects of manure are shown by experiments at Rothamsted and Woburn, England. At Rothamsted, one plot had received manure for 20 years, and none after that. Barley has been grown on this plot for 58 years, and still shows the effect of the manure applied 38 years ago. Thirty years after the last application of the manure, the crop of barley on the manured plot was twice as large as that which had never received any fertilizer or manure. At Woburn a plot which had received manure a few years continued for 25 years to give better yields than one which had received no manure.

Green Manures and Cover Crops.[1]—Green manures and cover crops are planted to be plowed under. It is of course more desirable to feed the crop and save the manure, thereby utilizing its feeding value and most of its fertilizing value, but this procedure is not always practicable.

The objects of green manure and cover crops are as follows:

(1) To supply organic matter to the soil.

[1] Farmers Bulletin 278.

(2) To prevent loss of plant food by leaching. The soil is covered with a crop instead of being left bare. The crop takes up most of the plant food in solution and prevents it being washed out of the soil.

(3) To secure nitrogen from the air for the use of succeeding crops. For this purpose, leguminous crops should be grown, and they must be infected with the proper organism.

Green manures should, if possible, be allowed to mature before being plowed under. A large mass of easily decaying matter may sour the soil and injure it for some years. Lands which are decidedly wet are also not benefited by green manures, as they may denitrify. An acid condition of the soil may be corrected by lime.

As a rule, it is best to follow green manures with cultivated crops. The tillage of such crops hastens the decay of the vegetable matter, and by aerating the soil, favors additional nitrogen fixation by the soil bacteria. Corn, cotton, potatoes, and heavy tobacco derive great benefit from green manures.

The following table shows the effects of green manures on crops compared with crops on the same soil which had no green manure.

Locality	Manure crop	No manure	Green manure
Illinois ...	red clover	35.7 (grown continuously)	55.1 bu. corn
Ottawa ...	clover	38.8 (1 year)	49.9 bu. oats
Ottawa ...	clover	29.0	37.6 bu. barley
Arkansas .	cowpeas	10.1 (continuous 4 years)	14.1 bu. wheat
Alabama ..	cowpea vines	837.0	1,533.0 seed cotton
Alabama ..	cowpea vines	12.4 bushels	22.8 bu. oats
Maryland .	crimson clover	52.8 bushels	72.3 bu. potatoes
Maryland .	crimson clover	67.8 bushels	102.2 bu. potatoes

Fallen leaves and stubble have some fertilizing value, even when the crop is cut for hay. For example, at the Alabama Experiment Station, 36.6 of the entire weight of the cowpea plant was found to be in the fallen leaves and stubble. The hay in one experiment contained 55.8 pounds nitrogen per acre, the fallen leaves and stubble 31.4 pounds.

Effects of Manure.—Some effects of manures are as follows: (1) They make clay soils more porous, in better tilth and more easily worked. (2) They make sandy soils more retentive of moisture. (3) They improve the physical character of the soil and make it better suited for plant growth. (4) They supply nitrogen and other plant food. (5) They supply organic matter which may aid soil bacteria to fix free nitrogen. (6) They are lasting in their effects.

CHAPTER XV.

SOURCES AND COMPOSITION OF FERTILIZERS.

When knowledge that certain elements are essential to plant life was first secured, the action of various elements were tested in practice upon soils in order to see which of these are not present in sufficient quantity. For example, at Rothamsted, plots are still fertilized with sulphate of magnesia. In the process of time, it was found that phosphoric acid, potash, and nitrogen were the substances needed for plant food, and a fertilizer is now generally defined as a substance which contains phosphoric acid, potash, or nitrogen, or a mixture of them, and is used as an application to the soil to promote the growth of plants. A further requirement is that the potash, phosphoric acid, or nitrogen be in such forms as to be readily taken up by plants. The value of the fertilizer is based upon the amount of these three substances it contains.

Fertilizers have other effects on the soil in addition to their supply of plant food. They may affect its acidity or alkalinity, its physical structure, etc. Substances which contain little or no phosphoric acid, potash, or nitrogen, and are used upon the soil for other reasons, are termed *amendments*. Lime, for example, is an amendment.

Nitrogenous Fertilizers.—Nitrogenous fertilizers are divided into two groups, inorganic and organic. The two inorganic materials, nitrate of soda and ammonium sulphate, may be directly assimilated by plants, though the ammonium sulphate usually undergoes some nitrification and is converted partly into nitrates. Organic substances, such as dried blood, cottonseed meal, tankage, etc., must first undergo changes in the soil, by which the nitrogen is converted into ammonia or into nitrates, or into organic compounds which can be assimilated by plants. The different nitrogenous fertilizers have different agricultural values, depending on the readiness with which they can be assimilated.

Inorganic Nitrogenous Materials.—*Nitrate of soda* is found in the rainless districts of South America mixed with dirt and common salt, as deposits termed caliche. It contains on an average

about 25 per cent. nitrate of soda. The best quality of caliche contains approximately 50 per cent. nitrate of soda, $NaNO_3$, 26 per cent. common salt, 6 per cent. sulphate of soda, 14 per cent. dirt, etc., insoluble in water, and about 4 per cent. magnesium sulphate and chloride, with small amounts of sodium iodide. The caliche is treated with hot water and the solution run into crystallizing vats. The crude nitrate of soda crystallizes out on cooling. Nitrate of soda is readily soluble in water, easily taken up by

Fig. 70.—Nitrate of soda, partly blasted up.

plants, and, unless taken up by plants, will be washed from the soil. It contains about 15 per cent. of nitrogen. It is often called *chile saltpeter*.

Sulphate of ammonia is a by-product obtained in the manufacture from coal, of illuminating gas, and of coke. A part of the nitrogen of the coal passes off as ammonia, and is removed by passing the gas through sulphuric acid, forming sulphate of ammonia $(NH_4)_2SO_4$. It contains about 20 per cent. of nitrogen. Ammonia is fixed by the soil, and is not as available to plants as

nitrates, or as easily washed out. It changes to nitric acid in the soil, and nitric acid and sulphuric acid unite with lime to form nitrates and sulphates. The use of ammonium sulphate tends to decrease the carbonate of lime in the soil, or to render the soil acid.

Calcium Cyanamide.—This substance is prepared by passing atmospheric nitrogen over calcium carbide. It decomposes slowly

Fig. 71.—Crystallizing pans with nitrate of soda.

in the soil, with the production of nitrates. Under the most favorable conditions, it appears to have a value equal to sodium nitrate, but if applied too soon before planting, or to acid humus soils, it may have injurious effects.

Organic Materials.—The organic nitrogenous fertilizers cannot be taken up directly by plants but must first be converted into ammonia or nitrates. Their value depends upon their content of nitrogen, and the readiness with which they undergo decomposition in the soil.

Dried blood comes from the large slaughtering establishments, and is of two kinds, red and black. The red dried blood results from drying at the temperature of boiling water, at which temperature it does not char. The black dried blood is dried at a higher temperature, and decays more slowly. Dried blood is one of the most concentrated organic nitrogenous fertilizers. It contains about 11 per cent. nitrogen. It decays quickly in the soil.

Dried meat or meat meal is obtained from rendering establishments, where the different portions of dead animals are variously utilized. It is rich in nitrogen, and, like blood, decays rapidly. It also comes from slaughter houses where the waste meat is kept separate from the tankage.

Dried fish or fish scraps come from two sources: first, the offal of fish canneries, and second, the fish pomace resulting from the extraction of oil from Menhaden or other fish. The latter product is more uniform than the former, containing 7 to 9 per cent. of nitrogen and 6 to 8 per cent. phosphoric acid. Fish unfit for eating may be caught, the oil extracted, and the residue prepared into fish guano.

Tankage consists chiefly of the dried animal wastes from the large slaughtering establishments; to some extent it comes from the garbage plants of large cities. It is very variable in composition, since it contains all parts of the carcass which cannot be used for other purposes—the bones, tendons, flesh, etc. Tankage varies so much that it is always sold in the trade on the basis of its composition, and each shipment is subjected to analysis. It contains 5 to 10 per cent. nitrogen and 6 to 15 per cent. phosphoric acid. As a rule the fat and gelatine are removed by treatment with super-heated steam. Garbage tankage is less valuable than slaughter house tankage. It contains approximately 3 per cent. nitrogen and 1.2 per cent. each of phosphoric acid and potash.

Cottonseed meal is prepared by grinding the cake left from pressing the oil from cottonseed kernels. It is one of the best vegetable fertilizers. It is an excellent cattle feed, and its most economical use takes advantage of both its feeding and its fertilizing values, by feeding the meal and saving the manure. It

contains 6 to 8 per cent. nitrogen, about 1.5 per cent. potash, and 2.5 per cent. phosphoric acid.

Cotton seed have approximately one-half the fertilizing value of the meal. They contain approximately 3 per cent. nitrogen and 1.2 per cent. each of phosphoric acid and potash.

Linseed meal contains less nitrogen than cottonseed meal. The demand for this product for feeding purposes makes it an expensive source of nitrogen in fertilizers.

Castor pomace is not useful as a cattle food. It is about as rich as linseed meal, and is a good fertilizer. It contains 5 to 6 per cent. nitrogen and 1.0 to 1.5 per cent. each of phosphoric acid and potash.

Bat guano is the excrement of bats, found to a limited extent in caves in Texas, Mexico, and Porto Rico. It is liable to spontaneous combustion, the residue being known as bat guano ash, which is not easily distinguished from bat guano. Bat guano is variable in composition, ranging from a compound rich in nitrogen to one rich in phosphoric acid. It contains from 2 to 12 per cent. nitrogen and from 1 to 8 per cent. phosphoric acid.

Hoof and horn meal is a by-product from the making of various articles from hoofs and horns. It contains about 14 per cent. nitrogen.

Slowly Available Nitrogenous Fertilizers.—These materials give up their nitrogen very slowly, so that they often have little or no effect upon the crop to which they are applied. In many States the use of these materials in mixed fertilizers is prohibited.

Leather scraps is a waste product from various factories, and is sold as raw leather, steamed leather, and roasted leather. It contains about 7 to 8 per cent. nitrogen.

Hair is a product from slaughter houses, containing 9 to 14 per cent. nitrogen.

Peat and muck may contain as much as 2 per cent. nitrogen.

Wool waste is a by-product from woolen factories.

Availability of Nitrogenous Fertilizers.—The nitrogen of nitrate of soda and ammonium sulphate may be taken up directly by plants, but the value of the other nitrogenous materials depends

upon the rapidity and extent with which they become changed to nitrates and ammonia in the soil. It is important to know the relative values of these materials. The measure of their value is the quantity of nitrogen which may be secured from them by plants under favorable conditions. This is termed availability.

Availability is based upon value to plants in pot experiments. For the purpose of comparing nitrogenous materials, a soil decidedly deficient in nitrogen is selected, mixed thoroughly, and an equal quantity placed in a number of pots. Each pot then receives an equal and abundant amount of phosphoric acid, potash, and lime if necessary. One set of pots (two or more) receives no nitrogen. The others receive an equal quantity of nitrogen, say 0.3 gram for example, in the form of nitrate of soda, sulphate of ammonia, cottonseed meal, or other substances to be tested. An equal number of seeds of equal weight are planted in each pot, and the crops are grown under the same conditions as regards moisture, air, light, etc. They are then harvested, and the quantity of nitrogen secured from each pot determined. This nitrogen comes from both soil and fertilizer. The quantity of nitrogen secured from the pots to which no fertilizer nitrogen has been added is subtracted from the others to ascertain how much nitrogen was secured from the fertilizer. The amount of nitrogen taken from one of the materials (usually sodium nitrate) is adopted as a standard, (equal to 100) and the results expressed in terms of this. For example, if 0.250 gram nitrogen was secured from sodium nitrate by the plants and 0.180 gram from cottonseed meal, the availability of the nitrogen of cottonseed meal would be 0.250 : 180 :: 100 : x, or equal to 72.

Considerable care is required in the conduct and planning of experiments of this kind. Two or more pots must be used for each material. Nitrogen must be the controlling factor in the growth of the crop, and, in order to be certain such is the case, it is best to have several sets of pots with different amounts of nitrogen, such as 0.3, 0.6, 1.2 grams per pot for example. If nitrogen is the limiting condition, as it should be, the amount of nitrogen taken up by the plants will be in proportion to the quantity

applied. If there are other limiting conditions, the series to which they apply should be rejected.

Some workers have taken the weight of the crop as a measure of the availability of nitrogen, but since the object of the work is to ascertain what proportion of the nitrogen of the fertilizer can be taken up under the most favorable conditions, it is obvious that the amounts of nitrogen recovered is the only correct measure. The nitrogen taken up by the crops is not necessarily in proportion to their weights. For example, Johnson, Britton, and Jenkins[1] secured the following results with oats:

Amount of nitrogen applied grams..	0.8	1.6	2.4	3.2
Ratio of nitrogen	10.0	20.0	30.0	40.0
Weight of crop grams.....	31.7	57.8	27.7	40.7
Ratio of crop.....	10.0	18.0	9.0	13.0
Nitrogen taken up (grams)	0.384	0.778	1.064	1.404
Ratio of nitrogen taken up.....	10.0	20.0	28.0	36.5

In this experiment, the quantities of nitrogen taken up are nearly in proportion to the amounts of nitrogen applied, but the weights of the crops are not.

Conditions which Affect Availability.—The conditions which affect nitrification also affect availability, since nitrification is a necessary process for the preparation of active nitrogen. The length of the growing season is an important factor; a long growing season being relatively more favorable to the slowly nitrified materials. If a crop is grown and harvested and then a second crop grown without any addition of fertilizer nitrogen, the slowly acting nitrogen will appear relatively more effective than if one crop only is considered. For example, Voorhees found the availability of fresh solid manure (compared with nitrate of soda equal to 100) to be 12 when one crop (oats) alone was considered, but 43 when the nitrogen in two crops, oats and millet, was taken.

On account of the effect of the conditions of the experiment, and also on account of the error inherent in the method of work, considerable differences in the availability of the nitrogen of fertilizers are observed by different workers. The following

[1] Report Connecticut Exp. Sta., 1893.

table gives some determinations made on some ordinary nitrogenous materials:

COMPARATIVE AVAILABILITY OF NITROGEN FERTILIZERS.

	Connecticut Station 4 seasons. 1894-7		Wagner 3 years	Pfeiffer et. al., 1895-7
	Maximum and minimum	Average	Average	Average
Nitrate of soda	100	100	100	100
Ammonium sulphate	—	—	—	87
Dried blood	60-78	69	69	85
Cottonseed meal	72-87	71	—	—
Fish	64-70	68	64	—
Bone meal	—	17	61	—
Horn and hoof	57-77	67	—	—
Horn meal	—	—	63	85
Tankage	49-73	66	—	66
Castor pomace	65-81	71	67	—
Linseed meal	69-74	70	—	—
Raw leather	0.0-1.9	1	20	—
Dissolved leather	55-76	65	—	—
Steamed leather	8.1-18.5	13	—	—
Roasted leather	7.1-10.2	9	—	—
Flesh meal	—	—	54	—
Wool dust	—	—	33	—
Green manure	—	—	68	—
Barnyard manure	—	—	32	46
Barnyard manure preserved with sulphuric acid	—	—	—	56

Comparative Availability.—The availability of nitrogenous fertilizers for different series of experiments made by the same investigator exhibit considerable differences. Some workers have studied only the effect upon the first one or two crops, while others take into consideration the effect on several succeeding crops. The results of the Connecticut Station[1] given in the table, were secured in three series of experiments with (1) corn, (2) oats and corn, and (3) corn, in 10 pounds artificial soil composed of coal ashes and 3 per cent. moss, the root and fertilizer residues remaining in the soil from year to year. A fourth series, with

[1] Connecticut State Station Report, 1897, p. 257.

oats and Hungarian grass was made on 25 pounds sandy loam. The results of Wagner were on small plots with summer rye, flax, summer wheat, and carrots, and are the average of 3 seasons. Pfeiffer and associates used 27 kgs. poor sandy soil, and the effect of the residues for two years was considered, which increased the value of stable manure decidedly.

Voorhees at the New Jersey Experiment Station[1] made experiments with out-of-door cylinders, 3 square feet surface area and 4 feet deep, with corn, oats, and millet, oats and corn. Consideration of the second crop in each case increased the availability of manure decidedly. Root residues and fertilizer residues probably remained for succeeding crops, unless washed out during the winter. Some of his results are as follows:

	Oats	Oats and millet	Oats	Average[2] 1898-1907
Ammonium sulphate	72.9	77.9	90.2	69.7
Dried blood	58.5	61.3	68.4	64.4
Fresh manure, solid	12.0	43.0	14.0	35.9
Solid manure, leached	12 0	46.0	10.0	38.9
Solid and liquid, fresh	58.0	88.0	40.0	53.0
Solid, liquid, leached	20.0	33.0	29.0	43.1

Biological Methods of Availability.—Since organic materials must be transformed into ammonia and nitrates before being taken up by plants, the quantity of ammonia and nitrates produced from a given amount of nitrogen in the soil, with not too short a period, may be used for comparing nitrogenous materials. The quantity of *nitrates* produced from 0.3 gram nitrogen in 500 gram soil in four weeks varied with different soils, and was not in proportion to the value of the materials, but the quantity of nitrogen converted into nitrates and ammonia was in proportion to the availability of the material. The following table gives some of the results.

[1] Report, 1901, p. 144.

[2] Voorhees and Lipman, Bulletin 221, New Jersey Station.

Fertilizer[1]	Percentage of added nitrogen converted into			
	Nitrates		Nitrate and ammonium	
	Soil No. 75	Soil No. 77	Soil No. 75	Soil No. 77
Cottonseed meal	8.2	20.3	51.5	39.4
Blood	6.6	23.1	56.4	43.9
Bone	18.6	17.6	20.7	23.9
Batguano	17.5	17.8	29.1	24.8
Excrement	—	9.6	—	9.9

Chemical Methods.—Chemical methods do not determine the relative availability of the material, but distinguish between substances of high and of low availability. Three methods have been proposed:

(1) Digest with pepsin hydrochloric acid, filter, wash, and determine nitrogen in the residue.

(2) Digest[2] with neutral permanganate of potash in a boiling water bath, filter, wash, and determine nitrogen in the residue.

(3) Distil with caustic soda and permanganate, and determine the ammonia which passes over.

Each of these methods has its advantages and disadvantages. Method (3) is not applicable to cottonseed meal. All the methods depend on differences in the resistance of the various materials to the reagents employed.

Influence of Conditions on Availability.—Various conditions affect the availability of nitrogen in fertilizers, such as acidity of soils, fineness of division of bone, etc.

Wheeler,[3] in an unlimed acid soil, found the availability of blood to be 45.5, and ammonium sulphate injurious, while on the same soil limed, their values were 90.3 and 45.5 respectively. Johnson, Jenkins, and Britton[4] tested the availability of nitrogen in bone of different degrees of fineness; for meal less than 1/150

[1] Fraps, Bulletin 106, Texas Station.

[2] See Street, Report Connecticut Exp. Sta., 1911, Fertilizers, p. 9.

[3] Bulletin 53, Rhode Island Station.

[4] Connecticut State Station Report, 1897, p. 257.

inch, compared with nitrate of soda as 100, it was 11.3; 1/150 to 1/50 inch, 8.5; and 1/25 to 1/50, 5.6.

Any agency which accelerates the transformation of organic bodies into assimilable compounds would increase the availability of the nitrogen. The temperature, nature of soil, and activity of the organisms in the soil would thus be of effect.

Agricultural Value.—The availability of a nitrogenous fertilizer is measured by the amount of nitrogen which plants can secure from it under the most favorable conditions. Availability does not necessarily represent agricultural value, or crop producing power in the open field, since other factors enter in the question, some of which are as follows:

(1) *Kind of Season.*—In a very wet season, nitrate of soda is less useful than other forms because it is liable to be washed below the reach of the roots and lost altogether unless applied just when needed, or on a heavy soil.

(2) *Kind of Crop.*—Some crops grow and develop quickly, while others grow for a comparatively long period. Quick-acting fertilizers like nitrate of soda or ammonium sulphate, would be more effective on the former than organic fertilizers, which must undergo change before their nitrogen is available. The slower-acting organic materials would be better for plants with a long growing period, unless a number of applications of the quick-acting fertilizers are made.

(3) *Season of the Year.*—The change from organic nitrogen to ammonia or nitrate takes place more readily as the temperature approaches 98° F. Hence the organic materials would be relatively less effective for winter crops than for summer ones. A material which gives excellent results when applied to a crop dur- a warm and moist season, might be very unsatisfactory when the season is short, cold, and dry.

Phosphatic Fertilizers.—Phosphatic fertilizers are of two kinds, crude phosphates, and treated phosphates.

Phosphates.—The more important crude phosphates are bone, bone tankage, bone black, rock phosphate, apatite, and Thomas

phosphate. Bat guano and guano ash also contain phosphoric acid.

Raw bones consist of mineral matter, which is chiefly phosphate of lime, and organic matter, which is partly fat and partly ossein, a nitrogenous body. The ossein decomposes in the soil, and increases the availability of the phosphoric acid of the bone. Bone contains 18 to 25 per cent. phosphoric acid and 3 to 5 per cent. nitrogen.

Raw bone meal is crushed or ground bone and its value depends largely upon its fineness of division. The more finely it is ground, the more rapid its action. Bone meal is a good fertilizer, but acts slowly.

Steamed bone meal is made from bone which has been steamed to remove the fat and the nitrogenous matter, the latter being made into glue or gelatine. The steaming makes the bone soft and crumbly, and the phosphoric acid is more quickly available than in raw bone. Steamed bone meal contains 22 to 29 per cent. phosphoric acid and 1.5 to 2.5 per cent. nitrogen.

Bone black is made by distilling or charring bones out of contact with air. It consists chiefly of phosphate of lime and charcoal, and is used for removing the coloring matter in the refining of sugar. It contains 32 to 36 per cent. phosphoric acid. Spent bone black is treated with sulphuric acid like phosphate rock.

Rock Phosphates.—Rock phosphates such as are used for manufacture of acid phosphate consist chiefly of calcium phosphate, though they contain a small amount of iron and alumina. They are found in South Carolina and Florida as nodules, pebbles, or boulders, and in Tennessee in veins and pockets. These rock phosphates range from 25 to 40 per cent. in phosphoric acid.

Rock phosphates containing excessive amounts of carbonate of lime or of oxides of iron or alumina, are not suitable for the manufacture of acid phosphates, though they may be used for direct application to the soil. The carbonate of lime consumes sulphuric acid, while the oxide of iron and alumina react with soluble phosphates, causing them to revert.

Rock phosphate is used to a certain extent as a fertilizer. When ground very fine, so the particles may float in the air, it is known as floats. It does not act as quickly as acid phosphate, and may give little results the first year. Some soil chemists[1] advocate the use of heavy applications of ground rock phosphate, together with liberal applications of manure or green crops plow-

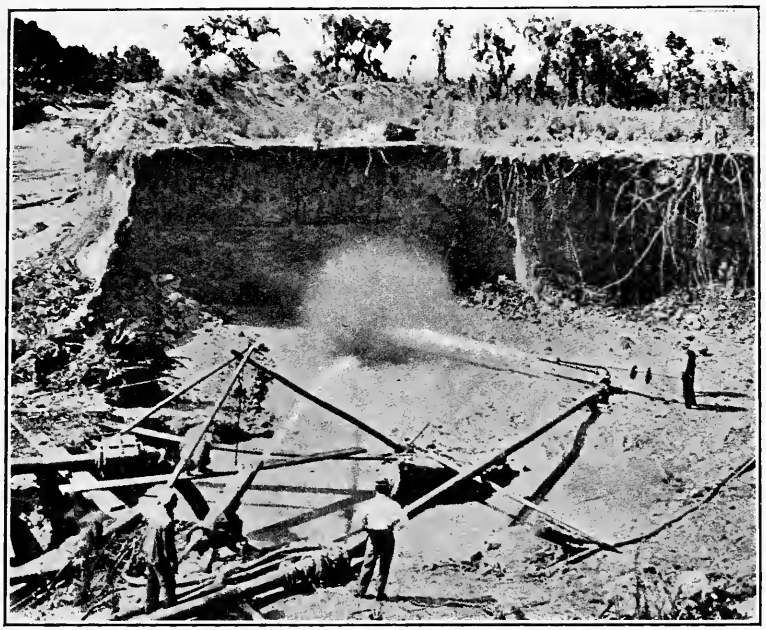


Fig. 72.—Mining pebble phosphate.

ed under, for staple crops like corn. According to the Ohio field experiments, acid phosphate used with manure gives larger net returns than rock phosphate.[2]

Apatite.—This is a crystallized calcium phosphate which occurs in quantity in Canada. The highest grade contains 40 per cent. phosphoric acid.

[1] Hopkins, Soil Fertility and Permanent Agriculture, p. 226.

[2] Circular 120, Ohio Station.

Thomas phosphate is a by-product from the manufacture of steel from phosphatic pig iron. It contains 15 to 20 per cent. phosphoric acid in connection with large amounts of lime and oxide of iron. The phosphoric acid was believed to be present as tetra-calcium phosphate, but according to Morison,[1] it is a silica phosphate of lime and ferrous iron. Thomas slag has its greatest effect upon soils rich in organic matter and poor in lime. It contains free lime, which may neutralize soil acids. It is a slow acting fertilizer.

Acid Phosphate.—It has been found by experiment that treatment of phosphates with sulphuric acid exerts a powerful influence upon their crop-producing power, and immense quantities are so treated for this reason. The rock is first ground to a powder, and treated with approximately an equal weight of sulphuric acid. The following reaction takes place:

(1) $Ca_3P_2O_8 + H_2SO_4 = H_3PO_4 + CaSO_4$.

(2) $Ca_3P_2O_8 + 4H_3PO_4 = 3CaH_4P_2O_8$.

Mono-calcium phosphate soluble in water is produced from calcium phosphate. The calcium sulphate, or gypsum, unites with water and causes the mass to harden. On standing the following reaction may take place, di-calcium phosphate being formed:

(3) $CaH_4P_2O_8 + Ca_3P_2O_8 = 2Ca_2H_2P_2O_8$.

This process is called reversion, and the di-calcium phosphate is termed reverted phosphoric acid. Reversion is also caused by the presence of iron and aluminium. The reaction is not clearly understood but may possibly be as follows:

(4) $2CaH_4P_2O_8 + Fe_2O_3 = Fe_2P_2O_8 + Ca_2H_2P_2O_8 + 3H_2O$.

The reverted phosphoric acid is assumed to have a value equal to water-soluble phosphoric acid. It is also termed citrate-soluble phosphoric acid, since it is dissolved by ammonium citrate in the chemical analysis of the fertilizer. Reversion by iron oxide and alumina produces ferric or alumina phosphate, both of which contain the phosphoric acid in an insoluble form. Some alumina phosphates are, however, citrate-soluble.

Phosphoric acid is thus present in an acid phosphate in three

[1] Jour. Agr. Sci., 1909, p. 161.

forms—water-soluble, reverted, and insoluble. Free phosphoric acid may also be present. The insoluble is the phosphoric acid insoluble in water and in neutral ammonium citrate. It is either the original tri-calcium phosphate of the untreated rock, or phosphoric acid which as reverted to the insoluble condition.

When the rock is treated with an excess of acid, some free phosphoric acid or sulphuric acid is present, which rots the bags and also causes the acid phosphate to be very sticky, especially in moist climates, so that it cannot be easily drilled in.

Available phosphoric acid is the sum of the reverted and water-soluble. In speaking of an acid phosphate, the phosphoric acid referred to is the available. Thus, if we speak of a 16 per cent. acid phosphate, we mean that it is guaranteed to contain 16 per cent. of available phosphoric acid, regardless of the total quantity present. Acid phosphate contains 12, 14, or 16 per cent. available phosphoric acid. The 12 and 14 per cent. grades are often made by mixing dirt or sand with the 16 per cent. phosphate. Such a mixture is not an acid phosphate, but is a mixture of acid phosphate and dirt or sand.

Treated phosphates may be made from phosphate rock, apatite, bones, bone ash, or bone black. Whatever the original material used, equal quantities of water-soluble or reverted phosphoric acid have equal values. That is to say, the water-soluble acid produced from apatite is equal in value, pound for pound, to that from bones.

Dissolved bone should be a treated phosphate prepared from bone. It should contain 2 to 3 per cent. nitrogen. Dissolved bone black is prepared from bone black.

Superphosphates.—Concentrated phosphates are prepared for long distance shipments, when the saving of transportation will more than pay the extra expense of manufacture. High grade phosphate rock is treated with dilute sulphuric acid, with the production of calcium sulphate and phosphoric acid:

$$Ca_3(PO_4)_2 + 3H_2SO_4 = 3CaSO_4 + 2H_3PO_4.$$

The calcium sulphate is filtered off, the solution of phosphoric acid concentrated and then mixed with phosphate rock.

$Ca_3(PO_4)_2 + 4H_3PO_4 = 3CaH_4(PO_4)_2$.

$2Ca_3(PO_4)_2 + 2H_3PO_4 = 3Ca_2H_2(PO_4)_2$.

The product contains 30 to 45 per cent. available phosphoric acid, depending on the degree of concentration of the acid and the kind of rock used.

Availability of Phosphatic Fertilizers.—The values of different forms of phosphoric acid are compared in the same way as nitrogen, namely, plants are grown under such conditions that phosphates are the limiting factor and a comparison made of the amounts of phosphoric acid taken up by the crops.

The availability of phosphoric materials depends upon other conditions in addition to the form of combination of the material, such as the presence of carbonate of lime or some other substances in the soil, the fineness of the material, the nature of the plant, etc. The effect of these conditions has not been studied to a great extent.

Potash Materials.—Potash is of relatively less importance than nitrogen or phosphoric acid, because potash is more abundant in the soil than either nitrogen or phosphoric acid, and, though larger quantities are removed, the potash is more likely to be returned. The potash taken up is most largely in the stems and leaves of plants, that is, the portion of the plant which is generally returned to the soil either directly, or indirectly in manure. When the entire crop is removed, the loss of potash is large. Potash is a very necessary constituent of fertilizers for some soils and some crops.

The chief commercial potash materials are tobacco stems, wood ashes, and the German potash salts, kainit, muriate of potash, and sulphate of potash.

Tobacco stems are a by-product from tobacco factories. They contain 6 to 8 per cent. potash, 2 to 2.5 per cent. nitrogen, and 3 to 5 per cent. phosphoric acid. They are used largely as an insecticide, but may sometimes be secured for a sufficiently low price to allow their use as a fertilizer.

Wood ashes are variable in composition, and their value depends upon the kind of wood from which they are made, and whether they are leached or unleached. Hard wood yields the most valuable ash. Ashes exposed to the weather lose most of their potash by leaching. Unleached ashes contain 4 to 8 per cent. potash and about 2 per cent. phosphoric acid.

Goessmann gives the following analyses of ashes:

		Average per cent.
Unleached—		
Potash	2.5 to 10.2	5.5
Phosphoric acid	0.3 to 4.0	1.9
Lime	18.0 to 50.0	34.0
Leached—		
Potash	about 0.5	—
Lime	about 40.0	—
Phosphoric acid	about 1.5	—

Coal ashes contain little plant food. Since ashes contain carbonate of lime and carbonate of potash, they are especially beneficial to acid soils, or those needing lime.

German Potash Salts.—The German potash salts are mined and concentrated in the region around Strassfurt, Germany, where they occur in immense beds at depths of from 1500 to 2500 feet below the surface. The important minerals found are as follows:

Carnallite, KCl, $MgCl_2$, $6H_2O$.

Kainit, K_2SO_4, $MgSO_4$, $MgCl_2$, $2H_2O$.

Sylvinite, KCl, $NaCl$, K_2SO_4, $MgCl_2$, $6H_2O$, $MgSO_4$.

Hartsalz, KCl, $NaCl$, $MgSO_4$, H_2O.

Carnallite, the chief source of potash, usually occurs mixed with rock salt and other minerals, and contains, as mined, about 9 per cent. potash. Kainit, as mined, contains about 30 per cent. rock salt and about 12 per cent. potash. Sylvinite is a mixture of sodium and potassium chlorides, containing 14 to 18 per cent. potash. The potash salts chiefly used in this country are kainit, muriate of potash, and sulphate of potash.

Kainit, correctly speaking, is a mineral composed of sulphate of potash and magnesia, K_2SO_4, $MgSO_4$, $MgCl_2$, $6H_2O$. The term is also used for crude potash salts containing not less than 12.4 per cent. potash, which may be crude kainit or mixtures of other crude salts. Since kainit is prepared from crude salts, no expense of manufacturing is attached to it. On the other hand, freight per unit of potash is higher than for the more concentrated potash salts. At a distance from the mines, the freight cost is greater than the manufacturing cost, so that the concentrated salts are cheaper. Since kainit contains chlorides, it is not suitable for use on tobacco or potatoes. Kainit is used as a preservative in saving stable manure, to check attacks of injurious insects, and as a remedy against cotton rust.

Muriate of potash is a concentrated potash salt prepared from the crude potash minerals by solution and crystallization. Various grades are prepared, ranging from 70 to 98 per cent. muriate of potash equivalent to 46.7 to 62 per cent. potash (K_2O).

Sulphate of potash is prepared by reaction between the muriate of potash and sulphate of magnesia, also found in the potash mines. The two are mixed in solution, and the sulphate of potash, being less soluble, separates out. Various grades are prepared, containing 45 to 53 per cent. potash (K_2O).

$$2KCl + MgSO_4 = K_2SO_4 + MgCl_2.$$

Double Manure Salts.—This is an impure sulphate of potash containing about 30 per cent. potash. It contains considerable amounts of sulphate of magnesia.

Forms of Potash.—The compounds of potash used in fertilizers are all soluble in water, and there is practically little difference in their availability. Some forms are, however, better adapted to some crops than others. Fertilizers free from chlorides are desirable for potatoes and tobacco, since chlorides make the potato less mealy and injure the burning quality of the tobacco.

Miscellaneous Fertilizing Materials.—The analyses of some miscellaneous fertilizing materials are given in the table. Most of

them are very variable in composition, but may furnish cheap sources of plant food.

	Phosphoric acid	Nitrogen	Potash
	Per cent.	Per cent.	Per cent.
Tobacco stems	2.0- 3.0	2.0-2.5	6.0-10.0
Tobacco stalks	3.0- 4.0	2.0-2.5	4.0- 5.0
Cured fish scrap	2.5- 8.0	2.0-6.0	—
Wool and horn waste	2.0-10.0	4.0-6.0	1.0- 3.0
Chicken manure, fresh	1.0- 1.5	0.5-0.8	0.5- 0.8
Chicken manure, dry	2.0- 3.0	1.0-1.6	1.0- 1.6
Sewage sludge	0.2	0.05	.05
Mussels, fresh	0.9	0.12	.13
Seaweed, fresh	—	2.0	—
Wood ashes	0.3- 4.0	—	2.5-10.2
Leached ashes	1.5	--	0.5

CHAPTER XVI.

PURCHASE AND USE OF FERTILIZERS.

Commercial fertilizers consist; first, of acid phosphate, cotton-seed meal, potash salts, and other commercial substances containing plant food; and secondly, of mixtures of these substances, made to secure a product of a desired composition. The mixture usually contains all three kinds of plant food, though a number of mixtures are on the market which contain only two, phosphoric acid and potash, or phosphoric acid and nitrogen.

Mixed Fertilizers.—Mixed fertilizers are of two classes—dry mixed and wet mixed. In *dry mixing,* the materials are weighed out, ground when necessary, mixed thoroughly, then passed through a screen so as to make them of uniform size. The nitrogen is generally in two or more forms, one highly available, the others less so. A *filler* is added when the sum total of the ingredients containing plant food do not make up the required weight to give the desired composition. Any substance which contains no plant food, or quantities much lower than the content of standard fertilizer ingredients, should be considered as a filler. The filler is usually sand or dirt, but sometimes objectional fillers are used, such as limestone, lime, or pyrite cinder, which contains oxide of iron. Small quantities of lime are sometimes used to dry the fertilizer.

In *wet mixing,* the organic nitrogenous material is first mixed with the sulphuric acid, then the phosphate rock is added, and the mixture is dumped out and allowed to harden as in the manufacture of acid phosphate. Potash salts or nitrate of soda, if either is used, is added while the product is being ground or otherwise prepared. In wet mixing, the nitrogenous material is to a certain extent acted on by the acid. There is no doubt that this treatment increases the availability of low-grade nitrogenous materials, but little experimental work has been done to show the availability of the product. Street[1] found the following changes in the nitrogen of one sample commercially treated in this way:

[1] Report Connecticut Exp. Sta., 1911, p. 14.

	Before treating	After treating (two days)
Ammonia nitrogen	6.5	14.3
Water-soluble organic nitrogen	7.8	57.7
Water insoluble organic nitrogen	85.7	28.0

In a pot experiment on oats and millet the treated nitrogenous material had an availability of 66 compared with that of nitrate of soda as 100, cottonseed meal 47, hair waste 29, garbage tankage 28, and peat 4.

Guarantee of Fertilizer.—A fertilizer is valuable on account of the quantity and kind of plant food it contains. The manufacturer buys on analysis, that is, he pays on the basis of the chemist's analysis of a fair sample of the shipment. The individual farmer, or one who purchases on a small scale, cannot afford to pay for a chemical analysis and can tell little or nothing about the substance by inspection. Hence the laws of most States in which fertilizers are used, provide for a guarantee of composition, penalties for failure to deliver guaranteed ingredients, and officials who are charged with the inspection and analysis of fertilizers. The simplest guarantee consists of a statement of the guaranteed minimum percentages of the available or total phosphoric acid, the nitrogen, and the potash. The total phosphoric acid is guaranteed only with respect to bone meal or rock phosphate, which contain little "available" according to chemical methods.

In some States, the term ammonia is used instead of nitrogen, and in one or two States, phosphorus and potassium instead of phosphoric acid and potash. Otherwise the latter terms are used the world over. A a varying guarantee, such as "2 to 3 per cent. potash," is allowed in some States, but is not desirable. Other States require a guarantee of water-soluble and reverted phosphoric acid. The use of the terms "potash as sulphate" etc., allowed in some States, is confusing to the average purchaser.

Commercial Valuation.—The commercial value of a fertilizer is the selling price of the plant food ingredients as determined by market and trade conditions. The agricultural value, or crop-producing power, often has no relation to the commercial or market value of the material. Thus it frequently happens that an element costs less in a highly available form than in a less available form. Organic nitrogen may cost more than nitric nitrogen, while the nitric nitrogen is more available and would have a greater crop-producing power if properly applied.

The commercial value is usually fixed by the cost of the plant food in the raw materials in ton lots at retail, and frequently at the seaboard. Cost of transportation must be added. Fluctuations in the values take place according to trade conditions.

An illustration of the commercial value is as follows: Suppose that 14 per cent. phosphoric acid costs $16.80 a ton. A ton contains 14x20 = 280 pounds available phosphoric acid, so that one pound costs 6.0 cents. This is the commercial or trade value.

If the commercial valuation of phosphoric acid is 6 cents, potash 6 cents and nitrogen 20 cents, it does not follow that a pound of nitrogen will give an increase of crop worth 20 cents, or that a pound of phosphoric acid will give a 6 cent increase, or that the effect will be in that ratio.

	1911 Cents per pound
Nitrogen in nitrates	16.0
Nitrogen in ammonia salts	16.0
Organic nitrogen in dry and fine ground fish and blood	23.0
Organic nitrogen in cottonseed meal and castor pomace	21.0
Organic nitrogen in fine ground bone and tankage and mixed fertilizers	20.0
Organic nitrogen in coarse bone and tankage	15.0
Phosphoric acid soluble in water	4.5
Phosphoric acid soluble in ammonium citrate	4.0
Phosphoric acid in fine ground bone and tankage	4.0
Phosphoric acid in coarse bone and tankage	3.5
Phosphoric acid insoluble (in water and in ammonium citrate) in mixed fertilizers	2.0
Potash in high grade sulphate and in mixtures free from muriate (chloride)	5.0
Potash as muriate	4.5
Potash in cottonseed meal and castor pomace	5.0

The preceding schedule of trade values is the one agreed upon by the Experiment Stations of Massachusetts, Rhode Island, Connecticut, New Jersey, and Vermont, after a careful study of prices ruling in the larger markets of the southern New England and middle States.[1]

These trade values are, as nearly as can be estimated, the average figures at which, in the six months preceding March 1, 1911, the respective unmixed ingredients could be bought at retail for cash in the larger markets (Boston, New York, etc.) They also correspond to the average wholesale prices for six months ending March 1st, plus about 20 per cent. in the case of goods for which there are wholesale quotations. The valuations obtained by the use of the above figures, it is claimed, will be found to agree fairly with the reasonable average retail price in the large markets of standard raw materials, such as nitrate of soda, sulphate of ammonia, dried blood, cottonseed meal, acid phosphate, muriate of potash, and sulphate of potash, etc.

The valuations used in Texas[2] for the season of 1911-12 are as follows:

	Cents per pound
Available phosphoric acid	6
Total phosphoric acid in bone and tankage	4
Nitrogen in mixed fertilizers, bat guano and cottonseed meal	20
Nitrogen in tankage	18
Potash	6

The valuation of nitrogen in Texas depends largely on the cost of cottonseed meal.

Calculation of Commercial Valuation.—Two methods are used, namely, the pound method and the unit method.

(*a*) The Pound Method.—Calculate the number of pounds of each ingredient per ton and multiply by the cost per pound. For example, in an 8.00 - 1.65 - 2.00 fertilizer:

0.08	×	2,000	=	160 pounds	×	6 cents	=	$9.60
0.0165	×	2,000	=	33 pounds	×	20 cents	=	6.60
0.02	×	2,000	=	40 pounds	×	6 cents	=	2.40
						Valuation per ton		$21.60

[1] Report Connecticut Exp. Sta., 1911, p. 7.

[2] Texas Station Bulletin No. 149.

(*b*) The Unit Method.—A unit is 1 per cent., and 1 per cent. of a ton is 20 pounds. Hence 20 times the value of a pound gives the value of a unit. To calculate the valuation, multiply percentage by value per unit. With nitrogen at 20 cents a pound, a unit costs $4.00. With potash at 6 cents, the unit costs $1.20. Using the example given above:

8.0	× $1.20	=	$9.60
1.65	× 4.00	=	2.60
2.0	× 1.20	=	2.40
	Valuation per ton		$21.60

The Meaning of Commercial Valuation.—The valuation of a brand of fertilizer by the State Fertilizer Control does not represent its proper selling price at the point of consumption. Neither should it be inferred that the ingredients in the brand in question have of necessity the commercial value indicated. It may be greater or less than is shown. The valuation system is based on the assumption that all brands compared are solely of high grade ingredients, an assumption which may be erroneous. "Valuations" should not be construed as showing the commercial worth of a given fertilizer, but the retail trade value at the seaboard, of amounts of nitrogen, phosphoric acid, and potash, equal to those contained in a ton of the brand in question, in unmixed, standard raw materials of good quality.

Valuations thus construed, while not infallible, are helpful:

(*a*) To show whether a given fertilizer is worth its cost from the commercial standpoint.

(*b*) As a common basis on which to compare the commercial value of different brands, enabling buyers to note whether prices asked are warranted by values contained, and aiding buyers to secure the most value for the least money.

Agricultural Value.—The agricultural value of a fertilizer is measured by the value of the increased crop produced by its use. It is variable, depending upon the availability of the constituent, the value of the crop, the needs of the soil, weather conditions, etc. For example, the agricultural value of a pound of water-soluble phosphoric acid is likely to be greater than that of

an equal amount of insoluble phosphoric acid, when used under the same conditions, because it is much more easily used by plants. But the water-soluble phosphoric acid may produce an increased yield of a crop on some soils and still not cause an increase in value sufficient to pay the cost of the application, while on another crop the application may result in a very great increase in value. On a soil which needs phosphoric acid its use may be profitable, while on one which does not need this form of plant food, it will have no effect. A fertilizer may produce a comparatively small effect upon a crop of high selling price, and yet be profitable; while on a crop of low selling price the increase may not offset the cost of the fertilizer.

Basis of Purchase.—Large sales of fertilizing material are usually at a certain price per unit. A unit means one per cent. on the basis of a ton. That is 20 pounds. For example, $1.00 per unit for phosphoric acid would be $1.00 for 20 pounds, or 5 cents per pound.

The ton basis of purchase is used for the sale of manufactured fertilizers. The purchaser must consider the guarantee, and valuation of the fertilizer before purchasing. For example, suppose fertilizer A is offered for $21.00 a ton, and fertilizer B for $24.00 a ton:

	A	B
	Per cent.	Per cent.
Nitrogen	1.5	2.00
Available phosphoric acid	6.00	8.00
Potash	1.00	2.00

Taking the valuations given elsewhere, we have the following:

	A	B
Nitrogen (20 cents per pound)	$6.00	$8.00
Available phosphoric acid (6 cents)	7.20	9.60
Potash (6 cents)	1.20	2.40
Total	$14.40	$20.00

There is thus a difference of $3.00 in the price and $5.60 in the valuation. Fertilizer B contains more value for the money. But the purchaser must consider the needs of his crop and his soil also, and not seek to secure merely the most value for the least money.

Home Mixing of Fertilizers.—By home mixing of fertilizers, we mean the purchase of the ingredients, and mixing them in the proportions to form the fertilizer desired. The preparation of acid phosphate from phosphate rock, or the grinding of bones or

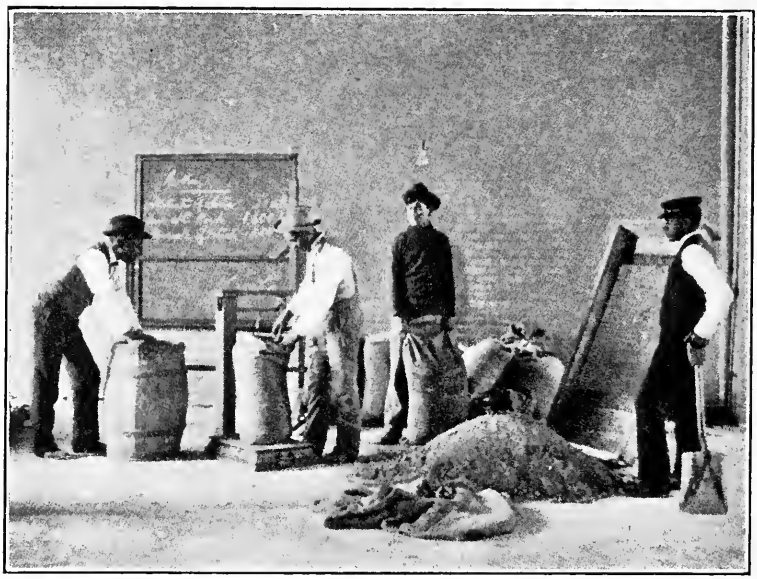


Fig. 73.—Instructing negro students in the home mixing of fertilizers.

other hard material, is most economically conducted on a large scale. In home mixing, then, we simply mix the ingredients which have already been prepared by grinding or otherwise.

The operation is very simple, the apparatus required being a clean floor, one or two shovels, and a sand screen, with meshes of about 4 to an inch. The materials are first weighed out, one by one, and piled on the floor, any large lumps being broken down

with a shovel. The pile is then shoveled over several times, and the mixture passed through the screen. Any lumps which fail to pass the screen are beaten up, and added to the mixture. The mixture is then shoveled over several times more. It is possible to prepare the mixture without any screen, but better results are secured with it.

The question whether home mixtures equal factory mixtures has been studied by a number of Experiment Stations in the following way: Samples of mixed fertilizer prepared at home were secured, and examined as to mechanical character, and the chemical composition was compared with that calculated from the amount and composition of the ingredients used. The mechanical condition was, as a rule, good and the chemical composition did not vary to any greater extent than samples of factory mixed goods as sold on the market. The New Jersey Experiment Station[1] says that it amply demonstrated in 1893, and corroborated in 1894, that farmers, with their ordinary farm appliances, can prepare mixtures that compare very favorably with purchased mixtures, both in mechanical condition and chemical composition. The Vermont and Maine Experiment Stations make similar statements. The Ohio Experiment Station[2] compared factory mixed goods with ready mixed goods in field experiments, on corn and wheat and found that the home mixed goods gave as good results as the factory mixed, or better. The New Hampshire Experiment Station[3] secured a similar result on potatoes. These experiments show that complete fertilizers can be prepared by home mixing, which are equal in every respect to the purchased article. It might sometimes happen that a mixture is difficult to prepare, owing to the fact that the materials have become lumpy and hard to beat up, but this is the exception and not the rule.

Whether or not it is profitable to make home mixtures depends upon the conditions. It is certainly more economical to buy the

[1] Bulletin No. 113.
[2] Bulletin No. 100.
[3] Bulletin No. 111.

unmixed materials in large lots for cash, and make mixtures, than to purchase mixed goods at retail, especially at credit prices. In this way one can secure somewhat more plant food for $20.00, than can be secured for $30.00, in a mixed fertilizer. The Experiment Stations of New York, Connecticut, New Jersey, North Carolina, and other States have demonstrated this to be a fact. When the unmixed materials are purchased in small quantity, at retail, it may or may not be profitable to make home mixtures. One can easily decide this question for himself by securing prices on mixed goods, and calculating the amount he would have to pay for the unmixed materials to make the same mixture.

Mixed fertilizers purchased direct from the manufacturer in carload lots may often be secured more cheaply than the home mixture can be made, since the cost of mixing is less to the manufacturer, who has appliances for economically handling large quantities.

It may be said further in favor of home mixtures, that one can know exactly what ingredients are used, whether they are of high, medium, or low grade. It is also easy to vary the mixture as desired, and to test the effect of different combinations upon the soil.

It has been objected to home mixing that the materials may not always be easily secured and that the mechanical condition is not as perfect as in the commercial mixed fertilizer. Mixed fertilizers are widely distributed and easily secured.

Calculating the Ingredients of a Mixture.—The calculation of the ingredients to make a fertilizer of a desired composition, is a simple mathematical matter. It is necessary, of course, to know the composition of the ingredients to be used. Suppose it is desired to make a fertilizer containing 8 per cent. available phosphoric acid, 2 per cent. nitrogen and 2 per cent. potash, using acid phosphate containing 14 per cent. available phosphoric acid, kainit containing 12 per cent. potash, and cottonseed meal containing 7 per cent. nitrogen, 2 per cent. available phosphoric acid, and 1.5 per cent. potash.

The desired fertilizer would contain, in 1,000 pounds, 80 pounds available phosphoric acid, 20 pounds nitrogen, and 20 pounds potash.

Since 1 pound cottonseed meal contains 0.07 pounds nitrogen, it would take $20 \div 0.07 = 286$ pounds cottonseed meal to furnish 20 pounds nitrogen. This 286 pounds would contain also $286 \times 0.02 = 5.7$ pounds phosphoric acid and $286 \times 1.5 = 4.3$ pounds potash.

The 80 pounds available phosphoric acid required, less 5.7 pounds, in the cottonseed meal, leaves 74.3 pounds to be secured from the acid phosphate. $74.3 \div 0.14 = 531$ pounds acid phosphate.

The 20 pounds potash required, less 4.3 pounds in the cottonseed meal, leaves 15.7 pounds to be secured from the kainit. $15.7 \div 0.12 = 131$ pounds kainit.

Then the desired ingredients to make 1,000 pounds of the fertilizer, would consist of:

	Pounds
Cottonseed meal	286
Acid phosphate	531
Kainit	131
Total	948
Filler	52
	1,000

It would thus be necessary to add 52 pounds filler to make the desired composition.

The ingredients for other fertilizer mixtures may be calculated in a similar way. In factory work, it is necessary to allow for variations in the composition of the ingredients by providing for a slight over-run. Otherwise, some of the mixtures may fall below guarantee.

Incompatibles in Fertilizer Mixtures.—Certain materials should not be mixed in making fertilizers, for the following reasons:

(1) Chemical reactions take place which result in the loss of nitrogen in the form of ammonia. For this reason, ammonium sulphate, guano, or barnyard manure should not be mixed with lime, ashes, or Thomas slag.

$$(NH_4)_2SO_4 + Ca(OH)_2 = 2NH_3 + CaSO_4 + 2H_2O.$$

(2) Chemical changes convert the phosphoric acid into less soluble forms. Acid phosphate should not be mixed with Thomas slag, lime or ashes.

$$CaH_4(PO_4)_2 + 2CaO = Ca_3\ PO_4 + 2H_2O.$$

Lime is, however, sometimes mixed with moist acid phosphate to improve its physical condition, so that the resulting mixture may be applied with a fertilizer drill.

(3) Certain mixtures will harden or cake and thus become difficult to distribute if kept for some time after mixing. Hence they should be applied soon after mixing. This applies to mixtures of lime or Thomas slag with potash salts, nitrate of soda, and kainit.

Conditions which Modify Use of Fertilizers.—These are: (1) Deficiency of soil; (2) Value of crop; (3) Character of crop; (4) Kind of rotation.

Deficiency of Soil.—A knowledge of the nature of soils with respect to the deficient elements is important, in order that those elements which are present in abundance may not be added to, but that they may be supplemented by such quantities of the deficient elements as to permit maximum profitable crops. This matter of soil deficiencies has been treated elsewhere.

An opinion as to the deficiency of the soil may be based on:

(*a*) The chemical composition of the soil.

(*b*) The behavior of the crop.

(*c*) Previous experience in the use of fertilizers.

(*d*) Field tests to ascertain needs of the soil.

The value of the crop is of importance in deciding the profitable application of fertilizers. Crops may roughly be divided into two classes: the first class have a relatively low commercial value per acre, the second have a high commercial value per acre.

Wheat, corn, oats, cotton, etc., belong to the first class. These crops remove large amounts of plant food in proportion to their value. For example, a ton of wheat removes 38 pounds of nitrogen, 19 pounds phosphoric acid, and 13 pounds of potash. With nitrogen at 20 cents and phosphoric acid and potash at 6 cents, the

Fig. 74.—Corn grown (A) continuously, (B) in five year rotation. Minnesota Station.

value of this plant food would be $9.50. Wheat at $1.00 per bushel would bring $33.33 per ton. The value of plant food in the grain is thus nearly ⅓ the selling price of the crop. Economy in the application of fertilizers is essential to profit with such crops. Nitrogen should be secured as much as possible from the air by legumes. Application of fertilizers should be based largely upon the needs of the soil.

Onions, asparagus, melons, cabbage, and tomatoes, are examples of crops which have a high value per acre. Such plants may be fertilized liberally, since the cost of even large applications of fertilizer is in small proportion to the value of the crop. Manure or legumes turned under should also be used on account of their beneficial effect on the soil.

Character of the Crop.—Plants vary in the quantity of plant food needed and in their ability to secure it. The season of growth is also of significance, since plants growing during the cooler period of the year are supplied with less nitrogen by the soil than those growing during the warm season.

While each plant possesses individual characteristics which distinguish it from others, they may be divided into groups which have somewhat similar characteristics, particularly as regards method and time of growth and their capacity for acquiring food from soil sources.

The *cereals* have a wide root growth and are able to acquire food from insoluble phosphates and potash readily. As, with the exception of Indian corn, their development takes place early in the summer before conditions are favorable for rapid nitrification, they are particularly benefited by nitrates. Corn does not usually require as large proportions of nitrogen as of mineral constituents, as its growth is made in the summer while the conditions are very favorable for nitrates.

The *grasses* resemble the cereals in their power of acquiring mineral food and are also benefited by application of nitrogen.

The *clovers* readily acquire mineral food, and also take nitrogen from the air.

Root crops (beets, mangels, turnips, carrots, Irish and sweet potatoes) cannot make ready use of the mineral constituents of the soil. Phosphates are especially useful for turnips, while beets and carrots require more nitrogen. Potash is particularly useful to potatoes.

Market garden crops have a high commercial value with a low fertility content. Hence they can be profitably supplied with an abundance of plant food. This supply also increases rapidity of growth, which is desirable, as the price is often in proportion to their earliness.

Fruit crops have a longer season of preparation and growth, and require a constant transfer of food from the tree to the fruit during the growing season. Food that will encourage a slow and continuous growth, rather than a quick one, is required.

The Kind of Rotation.—The order in which the crops follow one another in rotation, the kind of crop previously grown, and the treatment given it, are factors in intelligent fertilization. If the previous crop is a legume, and has left considerable residues, the succeeding crop stands less in need of nitrogenous fertilizers. A crop succeeding an exhaustive crop not liberally fertilized, may require liberal applications of plant food. The further removed the crop is from the legume crop, the greater its probable needs of nitrogenous fertilization.

Effect of Phosphoric Acid, Potash and Nitrogen on Plant Growth.—While the entire plant requires all forms of plant food, it may be said that nitrogen and potash stimulate the growth of leaves and stem, and phosphoric acid stimulates ripening of the fruit. An excess of nitrogen tends towards a large development of leaf and late maturity. Thus at Rothamsted, on the wheat plots which receive nitrogen and potash but no phosphoric acid, the grain hardly ripens at all. The use of phosphoric acid, however, hastens the maturity of the plant.

Fertilizer Experiments.—A great number of fertilizer experiments have been carried out by Experiment Stations, and other investigating agencies. The plans of the experiments vary a great deal, according to the crop to be tested, the information desired,

etc. The fertilizer is applied to plots varying from 1/50 to 1/2 an acre, but generally of 1/10 to 1/20 acre. The effect of the different applications is measured by the weight of the product on the different plots. The only variable should, of course, be the fertilizer. All other conditions should be the same for all the plots. The crop, however, is subject to other variables, such as differences in soil or subsoil, in stand, damage by insect pests, nearby trees or fences, etc. The best results are secured when the experiment is carried out on the same land for a number of

Fig. 75.—Tobacco, fertilized (A), and unfertilized (B). Ohio Station.

years to eliminate seasonal differences. It is also well for plots to be repeated a number of times in order to eliminate error due to inequalities of the soil.

In order to study the effect of variable soil on the crop, several experiments have been made in which a field of apparently uniform soil, bearing a crop under similar conditions in all parts, has been subdivided and harvested in separate small areas. Com-

parison shows the differences between these, and combination and comparison shows the differences of larger areas. For example, Morgan[1] selected a strip of land 112½ feet wide apparently uniform in texture, etc., which was planted in wheat first and then corn. It was measured off in strips 15x112½ feet, (about 1/25 acre) and the wheat or corn harvested separately from 63 plots which should thus be all alike. With the average yield at 100, the wheat crop varied from 65.0 to 130, and the corn crop from 169.3 to 42.3.

The plot yielding the lowest with wheat gave an average yield with corn, the highest with wheat 88.5 with corn. The plot lowest with corn was 113.7 with wheat, and the plot highest with corn was 100.4 with wheat. Thus the differences were not in the same direction with the two successive crops. Assuming that the theoretical yield depended upon the distance from the check plot, the following average errors were found:

	Average error Wheat	Average error Corn
	Per cent.	Per cent.
Every 10th plot a check	8.3	23.1
Every 5th plot a check	8.4	15.7
Every 3rd plot a check	6.4	15.7
Every 2nd plot a check	5.6	11.3

Assuming different treatments for the plots, the average and maximum error was found to be as follows:

	Average error		Maximum error	
	Wheat	Corn	Wheat	Corn
	Per cent.	Per cent.	Per cent.	Per cent.
Every plot different treatment	12.4	31.7	64.0	158.1
Every 12th plot the same	5.9	4.7	11.5	15.7
Every 6th plot the same	5.8	3.2	7.6	11.0
Every 2nd plot the same	5.0	2.3	3.8	4.7

[1] Proc. Am. Soc. Agri., 1909. See also Lyon, ibid., 1910, p. 35-38.

This experiment shows the great variation in the produce of two crops grown under apparently the same conditions in a field apparently uniform. It also shows that the error resulting from variations may be reduced by using a sufficient number of check plots, and by repeating the treatment on different plots. Great care must, therefore, be exercised in planning and conducting field experiments.

A similar experiment is reported by Smith from the Illinois Experiment Station, on 120 one-tenth acre plots of corn all treated alike for three years. In 1895 the yield varied from 11.4 to 50.2 bushels per acre, in 1896 from 48.5 to 103.9, and in 1897 from 44.2 to 80.2 bushels. The lowest yield in 1897 was on the plot which gave the highest yield in 1896. The maximum variation in adjoining plots was 18 bushels in 1895, 11 bushels in 1896, and 8 bushels in 1897.

Precautions in Making Fertilizer Experiments.—The following are some of the precautions[1] to be used:

(1) The greatest care should be taken to select land which is as uniform as possible in fertility. Lack of uniformity will give misleading results, and often render the experiments of little value.

(2) Level land should be selected if possible. If such cannot be had, the plots should run up and down the slopes, so that the washing by rain will not carry fertilizing materials from one plot to another.

(3) The experimental plots should be measured off carefully, and each plot indicated by stakes or stones.

(4) It is best to have the experimental plots long and narrow, because thus they will average up for uneveness of soil.

(5) It is best to separate plots by paths, to prevent roots of plants in one plot from feeding on the fertilizer supplied to adjoining plots.

(6) Avoid windy days in applying fertilizers, so that they may not be blown and scattered unevenly over the plots.

[1] Thorne, Circular 96, Ohio Exp. Sta.

(7) All the plots must be treated alike in every respect, except as to the amount and kind of fertilizer applied. The same kind

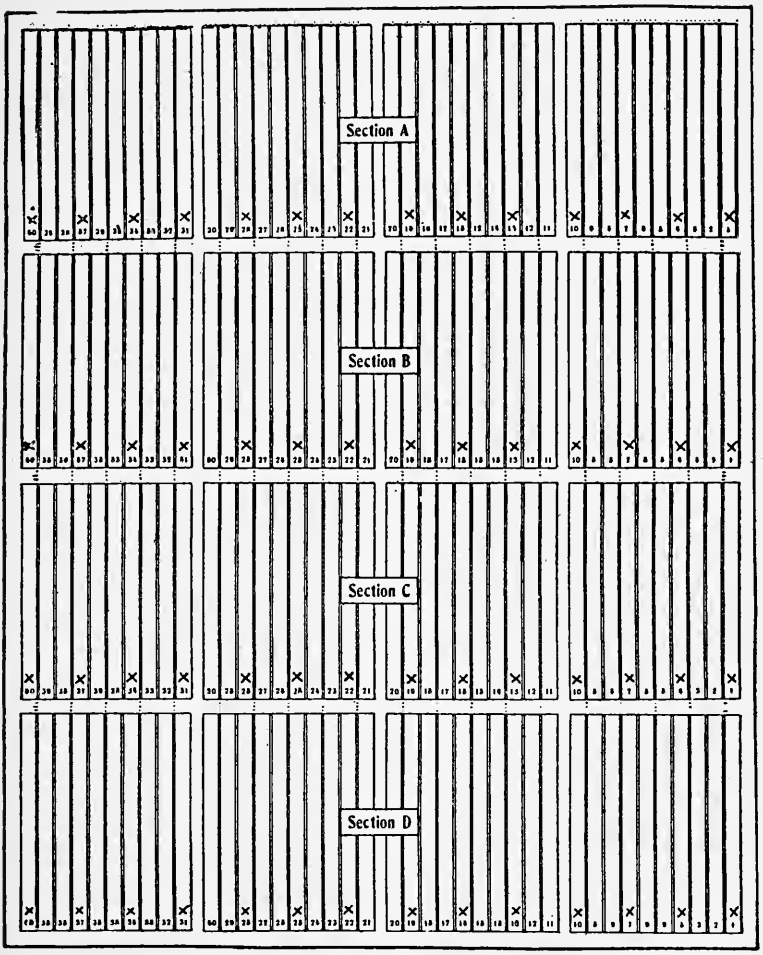


Fig. 76.—Plots for a fertilizer and rotation experiment, four sections of 40 plots each. The plots marked (X) are check plots. Ohio Station.

and quality of seed must be used over the entire area. The plowing or sowing on all the plots must be done the same day.

If part of the crop be planted before and part after a rain, the experiment may become valueless. Every precaution should be used to secure a full stand of plants, and if a uniform stand is not secured at the first planting, the whole field should be replanted. The same number of rows should be arranged on each plot, and the same number of hills and plants in each row, as nearly as possible. The plots should be plowed and cultivated alike, and whatever operation is needed on one experimental plot should be carried out uniformly on all the plots.

(8) The harvesting of the crop and weighing of yields must be accurate. A small mistake is multiplied many times when calculated to an acre.

(9) Provide liberally for check plots, and for plots on which repetition is made, so as to allow for inequalities of the soil.

At the Rhode Island Station,[1] the plots are 193.6 feet long by 30 feet wide, with 3 foot paths between, and roads at the end. Before the final harvest, the crop from a strip of land three feet wide on the sides and six feet wide at the ends, is cut and removed, this leaving exactly one-tenth acre to be harvested. This arrangement eliminates the error due to greater growth on the edges of the plot.

The importance of continuing field tests several years is shown by Thorne.[2] The results from the first year test on wheat is quite different from the ten year average:

Addition	Increase + and decrease — in yield of wheat in bushels per acre.	
	First year 1894	Average for 10 years
	bushels	bushels
Acid phosphate	—2.8	+ 6.5
Potassium chloride	+5.6	+ 1.3
Sodium nitrate	—1.21	+ 1.8
Acid phosphate and nitrate soda	—4.7	+11.4
Acid phosphate, potash and nitrate	—0.4	+14.8

[1] Report for 1904.

[2] Ohio Circular No. 96.

He also shows the effect of the fertilizer to increase from year to year, as per the following results on a plot receiving a complete fertilizer.

	Bushels per acre	
	Corn	Oats
Average 3 years	8.5	12.1
Average 6 years	11.2	14.5
Average 9 years	15.2	18.0

Thorne[1] corrects for variations in the soil by assuming that variations in fertility are regular from one check to the next. The difference between this method and the method of deducting

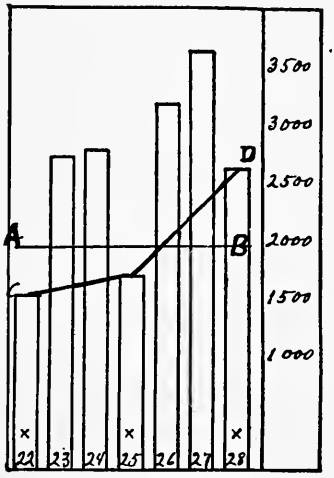


Fig. 77.—The same fertilizers give the same increase if the land decreases regularly (C D) from the checks, but not if the average of the checks (A B) is deducted. Ohio Station.

the average of all plots, is well brought out in Thorne's diagram. This represents four plots fertilized alike and three check plots. The increase in the average crop is regular if the soil varies uniformly, but the results are unconsistent if the average yield of the plots are deducted.

[1] Circular 96, Ohio Station.

Examples of Fertilizer Experiments.—The oldest and most famous fertilizer experiments are those at Rothamsted, England. Other important, long continued field experiments are those of the Ohio Experiment Station at Wooster, the Rhode Island Experiment Station, at Kingston, the Pennsylvania Experiment Station at State College, and the North Carolina State Board of Agriculture at Statesville, Red Springs, and Edgecombe, North Carolina.

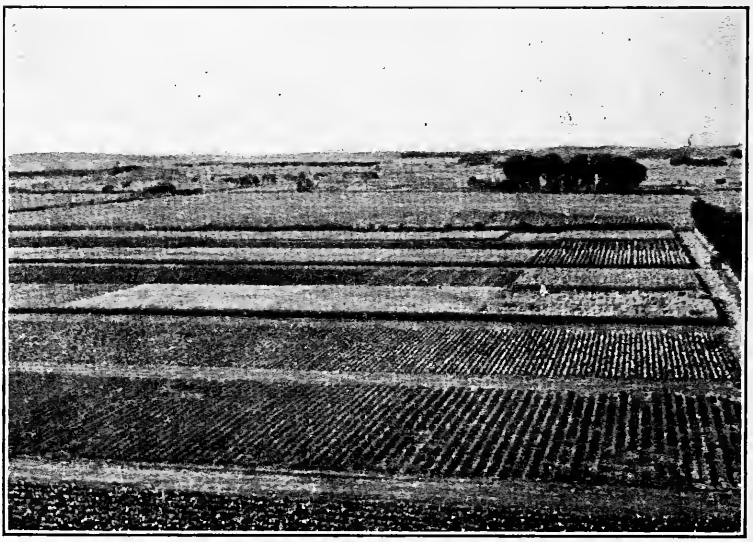


Fig. 78.—Experimental plot at the University of Nebraska.

The Rothamsted experiments were begun in 1848, and are important not only for having been long continued under the same plan, but also for the other valuable scientific studies made there. The Rhode Island Experiments are most important for their bearing upon soil acidity. The Ohio[1] experiments are very significant as regards rotation and manure.

The Rothamsted experiments comprise seven experimental fields: (1) crops grown in rotation, (2) wheat continuously

[1] Bulletins 110, 182, 183 and 184. Circular 120.

grown, (3) wheat alternating with fallow, (4) barley continuously, (5) potatoes continuously, (6) hay continuously, (7) experiments on root crops. Most of the plots are about ½ acre each. The plots are very long and narrow and separated by paths.

The following is part of the plan of the wheat experiments on Broadbalk field[1] with some of the results.

Plot	Application	Average bushels wheat, 51 years, 1851-1902.
2	Manure, 14 tons	35.7
3	Nothing	13.1
5	Minerals[2]	14.9
6	Minerals and 43 pounds nitrogen as ammonium sulphate	24.0
7	Minerals and 86 pounds nitrogen as ammonium sulphate	32.9
8	Minerals and 129 pounds nitrogen as ammonim sulphate	37.1
9	Minerals and 43 pounds nitrogen as nitrate of soda	(27.3)[3]
10	86 pounds nitrogen as ammonium sulphate	20.7
11	86 pounds nitrogen as ammonium sulphate and acid phosphate	24.0
12	Same as 11, plus sulphate of soda	30.0
13	Same as 11, plus sulphate of potash	31.5
14	Same as 11, plus sulphate of magnesia	30.1
15	Mineral plus 86 pounds nitrogen as ammonium sulphate (applied in autumn)	30.6
16	Minerals plus 86 pounds nitrogen in nitrate of soda	—
17 }	Minerals alone or 86 pounds nitrogen as ammonium	15.3[4]
18 }	sulphate alone in alternate years	40.4[5]
19	92.6 pounds nitrogen in rape cake	(28.0)[3]

Pennsylvania Experiments[6] at State College, were begun in 1882, on four fields of 144 plots of ⅛ acre, about 1¼ rods wide by 16 rods long. A four-year rotation of corn, oats, wheat, and hay of mixed clover and timothy is followed, each of the crops

[1] An Account of the Rothamsted Experiments, Hall.

[2] Minerals consist of superphosphate, with sulphates of potash, soda, and magnesia.

[3] Average for 10 years only.

[4] Average for minerals.

[5] Average for nitrogen.

[6] Report 1910-11.

being grown on one of the four fields every year. There are at least four plots of the same treatment, one in each field. The fertilizer is applied to the corn and wheat only.

Soil Treatment (Pennsylvania).

1–O	13–Plaster	25–PK
2–N	14–O	26–PNK(Na)
3–P	15–PK	27–PK2N(Na)
4–K	16–Manure 12	28–PK3N(Na)
5–PN	17–PNK	29–PK
6–NK	18–Manure 16	30–PNK(SO_3)
7–PK	19–PK2N	31–PK2N(SO_3)
8–Manure (prior to 1882)	20–Manure 20	32–PK3N(SO_3)
9–PKN	21–PK3N	33–Plaster
10–PK2N	22–CaO Manure 12	34–Limestone
11–PNK(Bn)	23–CaO	35–PNK(Bn)
12–PNK	24–O	36–O

N stands for 48 pounds nitrogen, 2N for 96 pounds, 3N for 144 pounds per acre. Blood was used in the first 24 plots, except No. 11, Nitrate of soda in plots 26-7-8 (marked Na) and sulphate of ammonia in plots 30-1-2 (marked SO_3). K signifies 160 pounds muriate of potash, P for phosphoric acid in dissolved bone black. Manure was used at the rate of 12, 16, and 20 tons per acre. Plaster is 640 pounds land plaster (gypsum). CaO is 2 tons caustic lime. Limestone is 4 tons ground limestone. Blood and bone were used on plots 11 and 35 for nitrogen and phosphoric acid, respectively.

Comparative Effects of Different Plant Foods.—In comparing the results of plot experiments, it is important to determine the effect of the individual fertilizing constituents, namely, of phosphoric acid, nitrogen, potash, or lime. The fertilizing constituents exert some influence upon the relative action of each other, but nevertheless it is often advisable to estimate the value of each independently. This can be done by subtracting the yield without the constituent in question from that with it. Thus the yield with phosphoric acid, potash, and nitrogen less that with phosphoric acid and potash gives the effect of nitrogen; by subtracting the yield with phosphoric acid and nitrogen we get the effect of

potash, and so on. Calculated in this way, the following table gives the increase in yield of ear corn produced by phosphoric acid, potash, and nitrogen respectively, from the Wooster Experiment Field of the Ohio Experiment Station.

	Bushels of ear corn produced by		
	Phosphoric acid	Potash	Nitrogen
Alone	6.6	4.0	3.9
With phosphoric acid	—	4.2	6.5
With potash	6.7	—	0.0
With nitrogen	9.2	0.2	—
With the two others	11.0	2.1	4.7
Average effect	8.4	2.6	3.8

These figures show the effect of phosphoric acid or potash or nitrogen, alone, or added to the other forms of plant food. On this particular soil phosphoric acid had the greatest effect, nitrogen next, and potash least.

Other studies and applications of the experiments are made, according to their character.

Value of Increase.—The profit in the use of different fertilizing ingredients depends chiefly on the cost of the fertilizer and the market value of the product. These two factors vary from year to year, so that the prices used must always be given, and must be carefully compared with present prices in studying the figures at later periods of time. The profit can be calculated by subtracting the cost of the fertilizer from the value of the increase in crop. We can also calculate the profit or loss due to the use of specific ingredients of the fertilizer as explained in the preceding section. For example, the following results were secured from seven years experiments with a rotation of corn, oats, wheat, and hay on the Strongsville Farm of the Ohio Experiment Station.[1]

[1] Bulletin 184.

	Total profit (+), or loss (—) per acre from the use of		
	Phosphoric acid	Potash	Nitrogen
Alone	+12.16	—5.97	—11.43
With phosphoric acid	—	—6.71	— 9.80
With potash	+11.42	—	—10.03
With nitrogen	+13.79	—4.57	—
With two others	+15.08	—3.28	— 6.37
Average profit	+13.11	—5 14	— 9.41

On this particular soil, with the amounts of fertilizers used and crops grown and at the prices given, phosphoric acid alone was profitable, potash and nitrogen being applied at a loss in both cases. On other soils and with other crops, different results would be secured. These figures are merely given to show the method of calculating. Additional expense due to handling the increased crop, and the fertilizer, should also be considered.

Systems of Fertilization.—There is a great diversity in soils, crops, climatic conditions, and other factors which modify the effect of fertilizers. Individuals must study their own conditions, try various combinations, and use such mixtures as give most profitable results under their conditions. Fertilizers which give good results are recommended in the various publications on the subject, but the application which will be the best and the most profitable will depend upon individual conditions.

Systematic use of fertilizers is more profitable than haphazard. The following are some of the systems[1] which are used. Every system should include a rotation of crops, with liberal use of manure or green crops plowed under.

1. *System Based on Influence of a Single Element.*—This system assumes that plants can be divided into three groups; one group most benefited by nitrogenous fertilizers, another by phosphatic, and the third by potassic. Nitrogen is said to be the dominant element for wheat, rye, oats, barley, meadow grass, and beet crops. Phosphoric acid is dominant for Indian corn, sorg-

[1] Voorhees' Fertilizers.

hum, sugar cane, turnips, and Swedes. Potash is the ruling ingredient for peas, beans, clover, vetch, flax, and potatoes. If the soil is fertile, the dominant element would be supplied to force a maximum growth of the crop, in such quantity as might be found necessary. If the soil is not fertile, moderate applications of the other plant foods are made, supplemented with more liberal additions of the dominant element.

2. *System Based on Necessity of an Abundant Supply of the Minerals.*—This system is based upon the fact that potash and phosphoric acid are cheap and not easily washed from the soil, while nitrogen is expensive and easily lost. According to the needs of the soil, a reasonable excess of phosphoric acid and potash is applied, sufficient to satisfy more than the maximum needs of any crop, and then the nitrogen is applied in active forms, such as nitrate of soda or sulphate of ammonia, and at such times as will insure the minimum loss of nitrogen and the maximum development of the plant. The phosphoric acid may be drawn from the cheaper mineral substances, such as ground bone, tankage, and ground phosphate rock.

This system is useful in building up a very poor soil when accompanied by a rotation which involves the use of legumes and manure.

3. *A System Based on the Amount of Plant Food Taken up by the Crop.*—According to this system, different plants are fertilized with phosphoric acid, nitrogen, and potash in the proportions in which chemical analysis shows them to exist in the plants. If care is taken to supply an abundance of plant food, this method may result in complete, though not economical, feeding of the plant, and may be profitable for crops of high value per acre, but for ordinary farm crops, it is likely to be unprofitable.

This system does not take into consideration the fact that one plant may have much greater power of taking up an element than another. Neither does it consider that the period or season of growth exercises some effect on the capability of a plant to acquire plant food from the soil. It may, however, be taken as a general rule that an application of easily available plant food

largely in excess of the requirements of the crop, is not advisable. Such an application is likely to lead to loss of plant food, either by percolation or by fixation.

4. *The Fertilizer is Applied to the Money Crop in a Rotation.*— In this system, the money crop is supplied with an abundance of plant food, so as to insure continuous feeding and maximum production. The remaining crops, or those immediately succeeding in the rotation, are nourished by the residues, with small applications of fertilizer, if necessary. If, for example, the rotation is cotton, corn, and cowpeas, the cotton would be liberally fertilized, the corn and cowpeas being allowed to feed on the residues.

Use of Nitrate of Soda.—Nitrate of soda is easily soluble in water, and distributes itself through the soil, and as the nitrogen can be easily taken up by plants, it is quickly effective. On the other hand, it is so soluble in water that it is easily washed from the soil by rains, and there may be loss from leaching when applied previous to the growth of the plant, or in too large quantities at the wrong time, or when heavy rains occur immediately after its application.

The best use of nitrate of soda[1] is secured when an abundant supply of potash and phosphoric acid is present. We have already seen that the size of a crop is controlled by the most unfavorable condition, and if potash or phosphoric acid are deficient, this deficiency cannot be overcome by the use of nitrate of soda.

The best use of nitrate of soda is also secured when it is applied to soils in good condition rather than to poor or worn out soils. Larger quantities may profitably be applied to good soils than to poor soils. Clods and lumps prevent a proper distribution of the material as well as a ready absorption of plant food, which are also necessary for good results. The application of nitrate of soda is especially advantageous for quick growing vegetable crops, where market quality is measured by rapid and continuous growth, and for those field crops which make their greatest development in spring, before the conditions are favorable for the change of the nitrogen in the soil into forms usable by plants.

[1] Bulletin 172, New Jersey Station.

Apply 100 pounds per acre on poor soils, 150 pounds on good soils, as a top dressing in the spring after the grass or crop is well started. For ordinary field crops, since nitrogen is so expensive, the increase in yield may not pay for nitrogen used in fertilizer.

Crops grown in the early spring, such as early spring forage, or spring wheat, oats, etc., may be unable to secure sufficient nitrogen from the soil to permit of rapid and maximum development.

The agencies which change organic into active nitrogen may not be sufficiently active to produce a sufficient supply of active nitrogen. Hence an application of active nitrogen in the form of nitrate of soda may cause great gains to take place. Some crops, as tomatoes, cabbage, potatoes, etc., must be grown and harvested early, in order to be highly profitable. Hence their growth must be forced at a time when the natural agencies are not very active.

According to bulletins of the New Jersey Experiment Station, the use of 150 pounds per acre of nitrate of soda has increased the wheat crop 9 bushels per acre. Early tomatoes were increased in value 50 per cent. by 150 to 250 pounds, early cabbage 40 to 80 per cent. by 400 pounds, musk melons doubled in value by 200 pounds.

Quantity of Fertilizer.—The applications of different quantities of the same fertilizer follows the law of diminishing returns. That is, the increase produced by each successive increment of fertilizer diminishes as the quantity of fertilizer increases. Thus the cost of the increment increases with the quantity of fertilizer. The fertilizer is profitable up to a certain point, after which the value of the increase is not equal to the cost of the additional amount of fertilizer. The most profitable quantity depends upon the character of the soil, the kind of crop and its value, and climatic conditions. The more valuable the crop, the larger the quantity of fertilizer which may be profitable.

As an illustration, we will cite the experiments conducted for four years by the New York (Geneva) Experiment Station[1] to ascertain the most profitable quantity of fertilizer for potatoes. The fertilizer used contained 8 per cent. available phosphoric acid,

[1] Bulletin 187.

4 per cent. nitrogen, and 10 per cent. potash, costing $25.00 per ton. The average of the four crops is as follows:

Pounds fertilizer per acre	Increase in fertilizer	Increase in yield due to increase in fertilizer	Cost of fertilizer for each additional bushel potatoes
		Bushels	
0	0	—	—
500	500	23.3	$0.27
1,000	500	20.9	0.30
1,500	500	11.2	0.56
2,000	500	6.0	1.04

The first 500 pounds fertilizer produced an increase of 23.3 bushels potatoes, a cost of 27 cents per bushel for fertilizer. The last 500 pounds produced 6.0 bushels at a cost of $1.04 per bushel for the fertilizer.

Secondary Actions of Fertilizers.—The supplying of available plant food is the primary action of fertilizers. They have other secondary actions upon the soil, which may not be unimportant at times.

Reaction.—Sulphate of ammonia leaves an acid residue in the soil, which unites with lime, increases the loss of lime, and may cause a soil not rich in lime to become acid. This has taken place at the Woburn (England) Experiment Farm, where the plot which receives sulphate of ammonia has become acid and will not grow barley. Addition of lime corrects the acidity.

Acid phosphate may also have a slight tendency towards causing soil acidity. Nitrate of soda leaves a basic residue in the soil, and hence has a tendency to correct acidity. Organic nitrogenous fertilizers do not affect the reaction of the soil.

Physical Structure.—Acid phosphate tends to flocculate a clay soil. Nitrate of soda tends to cause it to puddle or run together. Potash salts vary somewhat in their action, according to the nature of the soil.

Fertilizers Conserve Moisture.—Fertilizers may decrease transpiration and reduce the quantity of water required to produce growth. For example, Widstoe reports the quantity of water

transpired per 1 gram dry matter produced in one experiment on corn in pots as follows:

	Grams
No fertiiizer	1,012
Phosphates	735
Nitrates	555
Phosphate and nitrate	178

Bacterial action is undoubtedly affected by fertilizers, but to what extent or of what importance is not known.

It is claimed that the sulphate of lime which is present in acid phosphate may liberate soil potash and so render it available to plants. It is also possible that this sulphate of lime may supply plants directly with sulphur, but this is a matter which requires further study.

Whitney claims that fertilizers destroy toxic substances in the soil, but no direct evidence has been brought forward to show that such is the case.

Relation of Fertilizers to Losses and Changes of Plant Food.— When nitrogen, and, to a less extent, potash, is added to the soil, the loss due to percolation increases. This is shown by analyses of percolation waters from drain gauges or tile drains. See Chapter XIII. There is also an increased loss due to denitrification, which can be ascertained by analysis of the soil after a number of years, provided loss by percolation and cropping is also known. Little loss of phosphoric acid takes place, except possibly on very light sandy soils.

Fertilizers improperly used may diminish the fertility of the soil. Thus acid phosphate alone will give good results on some soils for a few years, but the increased crop increases the draft upon the nitrogen and potash of the soil. Unless provision is made to restore the loss of nitrogen and potash, the acid phosphate will become less and less effective. The same is true, though to a less extent, of fertilizers containing large percentages of phosphoric acid and small percentages of nitrogen and potash, such as a fertilizer containing 8 or 10 per cent. available phosphoric acid, 2 per cent. nitrogen, and 2 per cent. potash, such as are commonly used in the South for fertilizing cotton and corn.

Used in small quantities, these fertilizers tend to deplete the soil of nitrogen, unless provision is made to restore it otherwise. The use of such fertilizers in large quantity is not to be recommended, since a great deal more phosphoric acid is supplied than can possibly be utilized by the crop. If more fertilizer is used, it should be richer in nitrogen.

Effect of Fertilizer on Succeeding Crops.—The effect of fertilizer carried over to a subsequent year is shown in the experiments at Rothamsted. Plot 17 and 18 receive "mineral manure" consisting of superphosphate and sulphates of potash, soda, and magnesia one year, and 86 pounds nitrogen in sulphate of ammonia the second year. These applications have alternated for 51 years. The average results are as follows:

	Bushels of wheat per acre
Plot 5—mineral manure	14.9
(A) Plots 17-18 when mineral manure etc., is applied	15.3
(B) Plots 17-18 when sulphate of ammonia is applied	30.4
Plot 7—complete fertilizer	32.9

Thus plots 17-18 produce little more crops the year after the application of sulphate of ammonia (A) than plot 5 which receives no ammonia. Plots 17-18 produce nearly as much the year after the application of the phosphoric acid and potash, as they do in plot 7 which receives them every year. That is to say, the phosphoric acid and potash remain in the soil in an available form, so as to be useful to the next crop, while the nitrogen was leached out or otherwise rendered of little value to the plant.

Fixation.—It is commonly supposed that phosphoric acid and potash of fertilizers are fixed and rendered less soluble almost as soon as they are placed in the soil. This is not, however, the case. Some of the lumps of fertilizer are ¼ inch in diameter, and do not dissolve at once. When they do dissolve, diffusion is not a rapid process, and the soil particles nearest the fertilizer are brought in contact with the more concentrated solution, and fix larger proportions of it, than those farther away. Hence the fertilizer becomes the center of a zone of concentrated plant food, more dilute towards the outside. This

is even to some extent true of the easily soluble fertilizers, like nitrate of soda, for which the soil has little power of fixation, but still more so for the less soluble acid phosphates. In the case of organic nitrogenous materials, the particles become centers for the production of ammonia and nitrates, which may eventually be taken up by the rootlets as fast as they are formed. The well known fact that moderate applications of fertilizer are more effective when applied in the vicinity of the plant or seed than when applied broadcast, is evidence that the plant food does not become rapidly and uniformly distributed through the soil mass.

The Practice of Fertilization.[1]—There is such a variation in the needs of crops and soils for fertilizers, in the effect of climatic conditions, and previous treatment, upon their behavior towards fertilizers, that it is impossible to lay down specific rules for fertilization. The fertilizer which produces heavy yields of potatoes in the North, would not necessarily be suitable for the warmer climate, lighter yields, and earliness, associated with the same crop in the South. Onions grown on the sandy soils of Long Island, New York, require different treatment from those grown in the warmer climate and much richer soils under irrigation at Laredo, Texas. Applications suited to crops grown under favorable conditions of moisture may be unsuited to crops which may have to endure a period of drouth or mature on a moderate amount of moisture. The best that can be done is to lay down general principles, and to give the applications which have proved successful under certain stated conditions. The individual farmer must study his own conditions, with the help of his State Experiment Station, and learn by his own experience the most profitable applications for him to make. A few brief notes are made below on fertilizers for various crops.

Field Crops.—Rotation of crops, including legumes, to be turned under or fed and the manure saved, is essential to maintenance of fertility for ordinary field crops. Only in this way can nitrogen be secured cheap enough. Phosphates and potash may

[1] See Voorhees, Fertilizers; Van Slyke, Soils and Fertilizers; Bulletins of Bureau of Soils and of State Experiment Stations.

be purchased as necessary, together with supplementary small amounts of nitrogen. Field crops, especially grasses and clovers, utilize insoluble phosphates fairly well.

Corn.—A suitable rotation, including careful saving of all manure, together with the use of phosphoric acid, will maintain corn lands at a good level of productiveness, or increase the yields. The phosphoric acid may be supplied in 200 pounds per acre of acid phosphate applied annually, or 2,000 pounds of rock phosphate applied every five or six years. An application of nitrogen, such as contained in 200 pounds cottonseed meal, may also be effective. Potash is needed on some soils. The ordinary corn and cotton fertilizer used in the South contains 8 to 10 per cent. available phosphoric acid, 1.65 to 2.5 per cent. nitrogen, and 1 to 3 per cent. potash. It is used at the rate of 100 to 400 pounds per acre.

Oats.—Oats in a rotation often receive benefit from 100 pounds acid phosphate applied at the time of planting, and a top dressing of 100 pounds nitrate of soda when the plants begin their vigorous spring growth.

Wheat.—Same as oats. *Clover* uses much potash and is often benefited by 100 pounds acid phosphate and 50 pounds muriate of potash per acre. *Timothy* may receive the same application as clover and in addition a top dressing of 100 pounds nitrate of soda in the spring. *Alfalfa* requires lime and draws heavily on the potash of the soil. A good application is 200 pounds acid phosphate, 20 pounds nitrate of soda, and 100 pounds muriate of potash applied just before planting. This may be supplemented by 300 pounds acid phosphate and 200 pounds muriate of potash per acre per year. *Peanuts* are similar to alfalfa. A great deal depends on the soil.

Cotton.—Acid phosphate is used at the rate of 100 to 200 pounds per acre on land which produces a good stalk but does not fruit well. An application of 200 to 400 pounds cottonseed meal gives good results on many soils. The Georgia Experiment Station recommends for old worn uplands, a mixture of 1,000 pounds acid phosphate, 671 pounds cottonseed meal, and 296

pounds kainit applied at the rate of 400 to 800 pounds per acre. This fertilizer would contain 8 per cent. phosphoric acid, 2.4 per cent. nitrogen, and 2.4 per cent. potash. A rotation of crops including legumes should be adopted.

Truck Crops.—Rotation, manure, and heavy applications of fertilizers are used for truck crops.

Potatoes in New York receive 1,000 to 2,000 pounds of a fertilizer containing about 8 per cent. available phosphoric acid, 4 per cent. nitrogen, and 10 per cent. potash. In Texas good results are secured with a mixture of 800 pounds acid phosphate and 1,200 pounds cottonseed meal at the rate of 300 to 600 pounds per acre. *Sweet potatoes* in New Jersey receive 500 to 700 pounds of a fertilizer containing 3 per cent. nitrogen, 7 per cent. available phosphoric acid, 12 per cent. potash. In Georgia, 200 to 400 bushels per acre, according to soil and season, are secured with a mixture of 320 pounds acid phosphate, 360 pounds cottonseed meal, and 640 pounds kainit. *Early tomatoes* in New Jersey receive about 350 pounds acid phosphate and 200 pounds muriate of potash just before planting, a top dressing of 100 pounds nitrate of soda at time of setting out, and 100 pounds again three or four weeks later. *Onions* in New Jersey, do well on 1,000 pounds of a fertilizer containing 5 per cent. nitrogen, 6 per cent. available phosphoric acid, and 10 per cent. potash. In Texas, they do well on 1,500 pounds cottonseed meal, or 1,000 pounds of a fertilizer containing 5 per cent. available phosphoric acid, 5 per cent. nitrogen, and 5 per cent. potash. *Cabbage* may receive an application of 1,000 pounds of a fertilizer containing 4 per cent. nitrogen, 8 per cent. phosphoric acid, and 5 per cent. potash, supplemented by a top dressing of 100 pounds nitrate of soda and 100 pounds acid phosphate after the plants begin to grow when set out, and 100 pounds when the heads begin to form.

CHAPTER XVII.

CONSTITUENTS OF PLANTS.

For the purpose of ordinary agricultural analysis, the various compounds in plants and feeds are divided into six groups, each of which, with the exception of the first (water), is composed of a number of chemical compounds, varying in their nature and relative proportion according to the plant, or portion of plant, under examination.

These groups are as follows:

(1) *Water,* which is present in all feeds.

(2) *Ether Extract.*—This is the material extracted by ether and, in the case of seeds, is composed mostly of fats and oils, but it contains large quantities of substances other than fats in the case of hays, straw, and grass.

(3) *Protein.*—This includes all the nitrogenous constituents of the plant or feed.

(4) *Crude Fiber.*—This is the residue left on boiling the material with sulphuric acid and with caustic soda, a purely arbitrary method. It consists of cellulose, lignin, cutin, and other substances.

(5) *Ash.*—This is the residue left after the material has been burned, and consists of the substances not volatile at the temperature of the combustion. It consists chiefly of lime, magnesia, soda, and potash united with phosphoric acid, chlorine, carbon dioxide, sulphur trioxide, silica, and some unburned carbon.

(6) *Nitrogen-Free Extract* comprises all the other ingredients of the plants not included in the above groups. In estimating its quantity, the water, protein, ether-extract, crude fiber, and ash, are added together, and the sum subtracted from 100. The difference is the nitrogen-free extract.

Water.—Water is abundantly found in the green and growing portions of the plant, as in leaves, tender shoots, and immature seeds, but chiefly in the sap, in which it transports the materials used in the growth of the plants. The older portions of plants, such as the stems, and old wood, and the mature seeds, contain

smaller percentages of water. Substances such as hays, meals, etc., which are apparently dry, contain appreciable quantities of water.

The following table shows the percentages of water in some of the different classes of substances:

WATER IN PLANTS.

Green plants	Per cent.	Mature seeds and hays	Per cent.
Corn leaves	79.3	Corn fodder	42 2
Timothy	61.6	Timothy hay	13.2
Red clover	70.8	Red clover hay	15.3
Cowpea vines	83.6	Cowpea hay	60.7
Potatoes	78.9	Cowpeas (seed)	14.8
Sugar beets	86.5	Cotton seed	10.5
Turnips	90.5	Wheat (seed)	10.5
Green corn	75.4	Corn (grain)	10.9

Determination of Water.—The usual method is to dry the substance at the temperature of boiling water until it no longer loses weight (about five hours). The operation is conducted in a water-oven. This consists of a double walled box. The space between inner and outer walls is partly filled with water, and the inner chamber is heated by the steam. There are certain sources of error in the estimation of moisture which must be guarded against, some of which are as follows:

(1) *Absorption of Oxygen.*—Certain fats and oils absorb oxygen when heated in the air, thus gaining in weight; they may also become insoluble in ether. For instance, linseed oil, which occurs in linseed meal, absorbs oxygen with avidity. If materials containing such oils are dried in the air, the results on moisture are too low, and the ether extract is liable to be too low also. The remedy is to dry in a current of hydrogen, or of illuminating gas which contains no oxygen. Gasolene gas is not suitable.

(2) *Chemical Changes.*—At the temperature of boiling water, some compounds found in plants may undergo chemical change. The sugar in ripe fruits may be decomposed, or caramelized. For example, Snyder[1] found fresh tomatoes to contain 3.88 per cent.

[1] Bulletin 13, Minnesota Station.

sugar, while after drying at 100° C. only 2.04 per cent. was present, a loss of nearly 50 per cent., due to decomposition. The decomposition may produce volatile bodies, and thus give too high results for water.

Such materials should be dried in a vacuum, either at the ordinary temperature, or at a slightly elevated temperature. The drying may take place in a desiccator which contains sulphuric acid and has been exhausted with a vacuum pump.

(3) *Volatile Materials.*—Some substances lose volatile organic matter when dried at 100° in a current of air, or hydrogen.

Silage loses acetic acid and ammonium acetate. Tobacco loses moisture. Atwater found that meats and fish in drying lost 1 to 4 per cent. of their total nitrogenous material. Animal excrements, both liquid and solid, may lose nitrogen.

These losses may in some instances be avoided by drying in a vacuum. In others (as with urine and manure) analyses should be made on the fresh materials, and correction made for the loss.

Ether Extract.—The mixture of substances which is removed from a plant by extraction with ether is termed ether extract. It is often termed "fats and oils" and this expression is correct when reference to concentrated feeding stuffs is intended, as in such cases the ether extract is composed mostly of fats and oils. But when applied to hays or fodders, the term "fats and oils" is not correct, since the ether extract may contain 30 to 70 per cent. of substances which are not fats or oils, such as chlorophyll, hydrocarbons, and wax alcohols.

Ether extract is obtained from all plants, and nearly all parts of all plants. It is found in small quantities only, in roots and tubers, in somewhat larger quantities in hays, and straws, and in comparatively large quantities in certain seeds, such as the seeds of cotton, flax, peanut, soja bean, almond, and sunflower. These are called oil-bearing seeds. Certain fruits, such as the olive, are also rich in oil.

The ether extract of seeds may not be distributed uniformly, but may be concentrated in certain parts of the seed. Thus, while the entire grain of corn contains 5.5 per cent. of oil, the

germ contains about 27 per cent. oil, which may be expressed from it for commercial purposes. The ether extract of rye and wheat passes mostly into the bran along with the germ.

The percentage of ether extract in some of the different classes of materials is shown in the following table:

ETHER EXTRACT IN PLANTS.

	Per cent.		Per cent.
Beets	0.1	Corn, grain	5.5
Potatoes	0.1	Cowpeas	1.4
Corn fodder	1.6	Soja bean	16.9
Timothy hay	3.3	Peanuts	38.6
Wheat straw	1.3	Cotton seed	19.5
Wheat, grain	2.1	Cocoanut	57.4

Composition of Ether Extract.—The composition of the ether extract of some plants is contained in the following table:[1]

PERCENTAGE COMPOSITION OF ETHER EXTRACT.

	Neutral fat	Free fatty acid	Lecithin	Unsaponifiable matter
Hay	23.7	37.3	trace	30.8
Rye bran	78.3	16.4	3.3	7.6
Oats	59.2	35.4	0.8	2.7
Peas	58.6	11.2	27.4	7.4
Soja bean	95.5	1.2	1.3	1.5
Malt sprouts	24.7	30.1	3.6	34.5
Cottonseed cake	92.9	3.2	4.4	1.1
Potatoes	16.3	56.9	3.1	10.9
Beets	23.0	35.3	—	10.7

Stellwaag found, according to the above table, that nearly one-third of the ether extract of hay and malt sprouts is unsaponifiable matter. The ether extract of rye bran, peas, potatoes, and beets contain about 10 per cent. unsaponifiable matter. Over one-fourth of the ether extract of peas consists of lecithin.

According to Fraps and Rather,[2] who examined 18 hays and fodders, from 39 to 71 per cent. of the ether extract consists of non-fats, chiefly wax alcohols. The average percentage of non-fats was 58 per cent. of the ether extract.

[1] Stellwaag, Landw. Versuchs-stat.

[2] Bulletin 150, Texas Station.

PERCENTAGE COMPOSITION OF ETHER EXTRACT

	Unsaponifiable matter	Saponifiable matter
Alfalfa hay	67	33
Bermuda hay	65	27
Burr clover hay	60	39
Corn shucks	71	29
Johnson grass hay	60	38
Para grass hay	73	26
Millet hay	39	52
Average of 18	58	36

Determination of Ether Extract.—The substance is dried and extracted with water-free ether for sixteen hours. The ether is

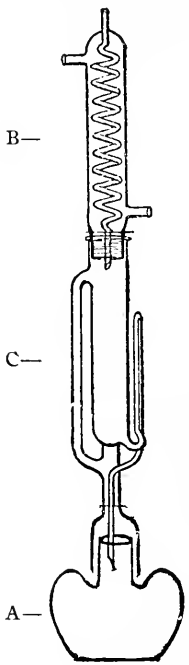


Fig. 79.—Fat extraction apparatus.

then distilled off, and the fat, after having been dried in a water oven, is weighed. A form of apparatus is represented in the

figure. The ether vaporized from the flask A is condensed by the cool water running through the condenser B and drops on the substance in C. It dissolves the ether extract and returns to the flask A, carrying the fat with it. It is then ready to be vaporized again and extract a fresh quantity of fat. When the exhaustion is complete, the ether is evaporated off and the fat is dried and weighed. This method is liable to several sources of errors, as follows:

(1) Loss of volatile fatty acids during the drying of the substance or of the extract.

(2) Oxidation of fats if the preliminary drying of the material is carried out in the air.

Fats and Oils.[1]—The largest and the most important portion of the ether extract of concentrated feeds is composed of fats and oils. Fats are solid at the ordinary temperature, while oils are liquid. They consist of ethereal salts, termed glycerides, which are compounds of certain fatty acids with the tribasic alcohol, glycerol, $C_3H_5(OH)_3$; thus, the fat palmitin $C_3H_5(C_{15}H_{31}CO_2)_3$, is the glyceride of palmitic acid $C_{15}H_{31}CO_2H$. When heated with alkalies, fats form glycerol and salts of the fatty acids, which are soaps. The process is called saponification. For example:

$C_3H_5(C_{15}H_{31}CO_2)_3 + 3NaOH = C_3H_5(OH)_3 + 3C_{15}H_{31}CO_2Na$.

Palmitin + Sodium hydroxide = Glycerol + Sodium palmitate.

All fats are lighter than water and insoluble in it. When pure, they are colorless, odorless, and neutral in reaction; under continued exposure to air, they begin to turn yellow, acquire a disagreeable odor and taste, and become acid—that is, the fat becomes *rancid*. The rancidity is due to partial decomposition of the glycerides, fatty acids being formed which are partly oxidized by the air to volatile substances having a disagreeable odor.

Oils are divided into the non-drying oils, and the drying oils. The drying oils, of which linseed oil may serve as an example, are oxidized by the air to solid, varnish-like masses. They contain linolin and linolenin, which are the glycerides of unsaturated acids. The non-drying oils do not undergo this change.

[1] See Lewkowitsch, Oils, Fats and Waxes.

Fats and oils are concentrated forms of nutrition, containing more nourishment and energy than any other nutrient in feeding stuffs (2¼ times as much as carbohydrates).

The following table shows the formula and composition of the principal glycerides which occur in fats.

Composition of Fats.

Name	Glyceride of	Formula
Butyrin	Butyric acid	$C_3H_5(C_3H_7CO_2)_3$
Caproin	Caproic acid	$C_3H_5(C_5H_{11}CO_2)_3$
Laurin	Lauric acid	$C_3H_5(C_{11}H_{23}CO_2)_3$
Caprylin	Caprylic acid	$C_3H_5(C_7H_{15}CO_2)_3$
Palmitin	Palmitic acid	$C_3H_5(C_{15}H_{31}CO_2)_3$
Stearin	Stearic acid	$C_3H_5(C_{17}H_{35}CO_2)_3$
Olein	Oleic acid	$C_3H_5(C_{17}H_{33}CO_2)_3$
Linolin	Linolinic acid	$C_3H_5(C_{17}H_{31}CO_2)_3$
Linolenin	Linolinic acid	$C_3H_5(C_{18}H_{29}CO_2)_3$

Palmitin, stearin, olein, linolin, and laurin are the principal glycerides which occur in fats and oils. Laurin, palmitin, and stearin are solid at the ordinary temperature, while olein is liquid. The consistency of a fat depends upon the predominating glycerides; the fats rich in palmitin and stearin are solid, while those rich in olein or linolin are liquid. Animal fats and oils contain the same glycerides as vegetable fats and oils.

The glycerides which occur in some fats and oils are named below:

Corn oil, chiefly olein and linolin, some stearin.

Cottonseed oil, chiefly linolin, also stearin, palmitin, and olein.

Sunflower oil, chiefly linolin.

Linseed oil, linolin, linolenin, isolenin, olein, stearin, palmitin.

Peanut oil, stearin, olein, linolin, arachiden.

Olive oil, chiefly olein, some palmitin and stearin.

Cocoanut oil, myrestin, laurin, palmitin, olein, caproin, caprylin.

Examination of Fats and Oils.—Different proportions of the same glycerides often occur in fats and oils of different origin. The following general methods are applied in the testing of fats

and oils. Specific tests may be made to detect certain oils, such as cottonseed oil.

The *specific gravity* is of importance.

The *index of refraction* is the measure of the extent to which the fat bends a ray of light passing through it. It affords a rapid method for testing the purity of some oils.

The *saponification value* is estimated by saponifying a weighed quantity of fat with a solution containing a known amount of alkali, and estimating the unused alkali by titration with an indicator and an acid of known strength. It is usually expressed in terms of milligrams of alkali neutralized by one gram fat.

The *volatile acids* are estimated by saponifying a weighed quantity of fat, liberating the fatty acids with a non-volatile acid, and distilling off the volatile acids with water. The distillate is titrated with alkali of known strength. This method is especially valuable for butter, since it is the only ordinary fat which contains glycerides of volatile fatty acids.

The *iodine* value is estimated by treating a weighed amount of fat with a solution containing a known amount of iodine. After sufficient time, the uncombined iodine is titrated and so estimated. The iodine combines with the unsaturated fats, and not with the saturated, so that the quantity of iodine absorbed depends on the quantity, and the condition of unsaturation of the fats present. The iodine number is the milligrams of iodine which combine with one gram of oil. The iodine number is a valuable index to the nature and purity of many oils.

Free fatty acids are often present in the ether extract. If the substance is old, and the fat in it has become rancid, a large part of the ether extract may consist of free fatty acids. They come from the hydrolysis or decomposition of the fats into fatty acids and glycerol. If acids of low boiling point are present, the free acids are partly volatilized when the substance is dried before being extracted with ether, or when the ether extract is dried. They are best determined by extracting the substance without drying, and titrating the etheral solution with a standard solution of caustic potash, with the addition of alcohol.

Lecithins.—These are wax-like bodies which resemble fats in some respects. They contain nitrogen and phosphorus. Like fats, they are saponified by alkalies. When saponified they yield a soap, cholin, phosphoric acid, and glycerol. The quantity of lecithin in the ether extract is calculated from the amount of phosphoric acid found in it. The magnesium pyrophosphate multiplied by 7.25 is assumed to represent the lecithin. Calcium and magnesium phosphates have, however, been found in the ether extract of plants, their presence being attributed to the presence of metallic glycero-phosphates soluble in ether. When these substances are present, the amount of lecithin in the fat is less than the amount calculated from the phosphoric acid present.

Lecithin is not entirely extracted by ether from plant substance, but is completely extracted when the ether extraction is followed by extraction with absolute alcohol. If the alcoholic solution is evaporated at 40-50° C. and the residue taken up with ether and purified by shaking with water, the lecithin can be obtained fairly pure.

Leguminous seeds are relatively rich in lecithin; the cereals (wheat, rye, and corn) contain much less. The table below shows the lecithin content of some substances:

LECITHIN IN PLANTS.

	Per cent. in dry matter
Young grass	0.45
Young vetch plants	0.86
Yellow lupine seeds	1.55
Soja bean	1.64
Peas	1.23
Wheat	0.65
Rye	0.57
Corn	0.74
Sunflowers	0.44
Vetch	0.98

The alcoholic extract contains not only lecithin, but other organic compounds containing phosphorus, some of which contain sugar. Lecithin is of considerable value to the animal and

also to the plant. It aids in the assimilation and transportation of the fat.

Hydrocarbons are compounds of hydrogen and carbon. They have been detected in the unsaponifiable portion of the ether extract of plants. The ether extract of meadow hay contains a hydrocarbon, probably $C_{27}H_{56}$. Tobacco contains 1 per cent. of the hydrocarbons $C_{31}H_{64}$ and $C_{27}H_{56}$.

Wax Alcohols.—The unsaponifiable matter consists of phytosterol and other alcohols. *Phytosterol* $C_{26}H_{34}(OH)$ is a solid alcohol which crystallizes from alcohol in glistening plates. It gives characteristic color reactions with certain reagents.

The separation of phytosterol and hydrocarbons from the fats is based upon the fact that while alkalies act upon fats to form compounds soluble in water (soaps), the phytosterol or hydrocarbons are not affected. The ether extract is saponified, and the soap extracted with ether, which dissolves the phytosterol and hydrocarbons. The etheral solution is evaporated, and the phytosterol purified by crystallization from alcohol.

Wax alcohols are found in considerable proportions in the ether extract of hays and straws. They are digested to a certain extent by animals, though not so well as fats. The alcohols present are probably myricyl alcohol $C_{30}H_{61}OH$, and other similar alcohols of lower molecular weight.

Chlorophyll.—This is the green coloring matter of leaves. It contains nitrogen. It is soluble in ether, and gives a green color to the ether extract from hays and green plants. Its exact composition is unknown. When the ether extract containing chlorophyll is saponified, and the unsaponified material is extracted by means of ether, the chlorophyll remains with the fatty acids and colors them green.

Protein.—Protein is the nitrogen of the plant multiplied by 6.25 and includes all the nitrogenous compounds of feeding stuffs. Protein includes amides, alkaloids, and inorganic nitrogen compounds (if present). Protein is found in all parts of all plants, as it is necessary to the life and growth of the plant. It is transferred from the stem and leaves of plants to the seed when the

plant matures. Protein is especially abundant in leguminous plants, and in seeds, particularly the seeds of legumes. The following table shows the amounts of protein in some vegetable substances:

PROTEIN IN VEGETABLE MATERIALS.

	Per cent.
Corn fodder, green	1.8
Potatoes	2.1
Onions	1.4
Timothy, green	3.1
Red clover, green	4.4
Corn, grain	10.5
Wheat, grain	11.9
Cowpeas, grain	20.8
Corn fodder	4.5
Timothy hay	5.9
Red clover hay	12.3
Cowpea hay	16 6
Soja beans	34.0

The nitrogenous constituents of agricultural plants may be divided into the four following groups: (1) proteids; (2) amides and amido acids; (3) inorganic compounds; (4) miscellaneous bodies; which include alkaloids, lecithin, chlorophyll, etc. Proteids and amides are of common occurrence in agricultural products; the other bodies, while of some importance, are of less general occurrence.

Proteids.—Proteids are complex bodies of unknown high molecular weight and unknown constitution. They contain carbon, hydrogen, oxygen, nitrogen, sulphur, and sometimes phosphorus. Proteids are exceedingly important, being necessary to the life of both plants and animals. The flesh of animals is composed largely of proteids, which are derived from vegetable proteids. When split up, proteids yield various amides, amido compounds, and other bodies. This splitting up takes place during digestion, and the digested constituents are reunited in the animal body to form animal proteids, which are different from the original vegetable proteids. The splitting up also takes place in the germination of seeds, when the reserve proteids are broken up into asparagin and other bodies, and used in the production of new tissue in the growing portions of the plant.

Classes of Proteids.[1]—The proteids are divided into three groups; simple proteids, conjugated proteids, and derived proteids.

I. Simple Proteids.—(*a*) *Albumins.*—Albumins are soluble in water and are not precipitated by sodium chloride, or magnesium sulphate. They are coagulated and made insoluble by heat. The best example of an albumin is the white of an egg.

(*b*) *Globulins.*—Globulins are not soluble in water, but are soluble in solutions of sodium chloride, and other neutral salts. They are precipitated by removing the salts, or by saturating the solution with salts.

(*c*) *Protamins* are proteids soluble in alcohol. Several have been isolated. Gliadin is found in wheat; zein, in Indian corn, etc.

(*d*) *Glutelins.*—These are not soluble in water, salt solutions, or alcohol. The glutenin of wheat is the only well characterized representative of this group yet obtained, though there are indications that they may be present in other cereals.

(*e*) *Albuminiods,* (*f*) *Histones,* and (*g*) *Protamines* have not been found in plants. They are animal proteids.

II. Conjugated Proteids.—Coagulated proteids are complex proteids which can be split up into proteids and other bodies. Nueclo-proteids, formed from nucleic acid and protein, have been isolated from some plants. Glycoproteids may be split up into proteids and carbohydrates. Phosphoproteids contain phosphorus.

III. Derived Proteids.—Derived proteids are produced from proteids by the action of acids, alkalies, alcohol, or digestive juices. The three important groups are proteoses, peptones, and peptides.

Proteoses.—Proteoses are soluble in water, and are not coagulated by heat, differing in this respect from albumins. They are *diffusable.*

Peptones.—Peptones are very easily soluble in water, and are not precipitated by heat, by neutral salts, or by nitric acid. They are precipitated by tannic acid, by absolute alcohol, and by picric

[1] Osborne, The Vegetable Proteins.

acid. Proteoses and peptones are formed in the digestion of proteids within the animal body, by the action of the juices of the stomach (the gastric juice), which contain *pepsin,* upon them.

Proteids in Plants.—The names and occurrence of some plant proteids are as follows:

Legumin, which is found in considerable quantity in seeds of pea, horse bean, vetch, and lentil.

Vignin, the chief protein of the cowpea.

Glycenin, a globulin, chief protein compound of soy bean.

Gliaden, soluble in alcohol of 70-80 per cent., the most abundant protein of wheat kernels.

Hordein, soluble in alcohol, found in barley.

Zein, most abundant in corn, easily soluble in alcohol.

Vicilin, a globulin found in pea, lentil and horse bean.

Composition of Proteids.—The proteids vary in composition and properties. The percentage composition of some important vegetable proteids is given in the following table:[1]

	C	H	N	S	O
Globulin, cottonseed	51.71	6.86	18.30	0.62	22.51
Legumin, vetch	51.72	6.95	18.04	0.39	22.90
Hordein	54.29	6.80	17.20	0.85	20.86
Globulin, wheat	51.03	6.85	18.30	0.69	23.13
Gliadin, wheat	52.72	6.86	17.16	1 03	21.73
Glutenin, wheat	52.34	6.83	17.49	1.08	22.26

The factor 6.25 used for proteids requires 16.00 per cent. nitrogen. The above proteids contain from 17.20 to 18.30 per cent. nitrogen.

Amides and Amido Compounds.—Amides, as distinguished from proteids, are nitrogenous compounds of known molecular weights and known constitution. They have little value in animal nutrition.

In seeds they occur only in small quantity. They are more abundant in leaves and the growing parts of plants, and are particularly abundant in germinating seeds. Nitrogenous material is converted into amides for the purpose of transportation through

[1] Osborne, The Vegetable Proteins, p. 49.

the plant. Amides are also formed from proteids by the action of acids, or the digestive juices of animals, or by other agencies.

The most important amido compounds are leucin, tyrosin, phenyl-amido-proponic acid, asparagin, and glutamin. Of these asparagin is relatively the most common and most abundant. It has the formula $C_2H_3(NH_2)(CONH_2)(COOH)$. Leucin, tyrosin, and phenyl-amido-propionic acid are amido-acids; that is to say, they are acids in which the amido group NH_2 has replaced an atom of non-acid hydrogen. Thus leucin, $C_5H_{10}(NH_2)CO_2H$, is derived from capronic acid, $C_5H_{11}CO_2H$, by replacing an atom of hydrogen by NH_2.

Determination of Proteids and Amides.—An accurate method for this determination is much to be desired. The usual method consists in boiling the substance with water and precipitating the proteids with copper hydroxide. The nitrogen in the precipitate multiplied by 6.25 is supposed to give the proteids. The difference between the precipitated nitrogen and the total nitrogen, is the amide nitrogen.

PROTEIDS AND AMIDES IN PLANTS.[1] (IN DRY MATTER.)

	Proteids	Amides
Soja bean hay	11.8	7.0
Cat tail millet	8.3	4.7
Sorghum fodder	7.9	3.1
Peanut vine hay	9.1	2.4
Cottonseed meal	41.7	0.6
Crimson clover hay	13.9	3.1
Corn meal	10.1	—
Green rape	16.2	0.8
Timothy hay	4.4	1.2
Cottonseed meal	47.2	0.6
Timothy hay No. 2	5.3	0.7

The preceding table shows that the protein of seeds consists mostly of proteids, but a considerable part of the protein of hays and fodders may consist of non-proteid materials. The percentage of nitrogen in the amido compounds we have mentioned, is given in the following table:

[1] Bulletin 172, North Carolina Exp. Sta.

NITROGEN IN AMIDO COMPOUNDS

	Per cent.
Asparagin	21.37
Glutamin	19.31
Leucin	16.87
Phenyl-amido-propronic acid	8.48
Tyrosin	7.73

Considering that asparagin is the most common amide in plants, it is evident that the factor 6.25 (which requires 16 per cent. nitrogen) is too high. A percentage of 21.37 nitrogen requires the factor 4.68.

Inorganic Nitrogenous Bodies.—Growing plants sometimes contain appreciable amounts of nitrates or ammonia. Very little is found in ripe seeds or plants. The nitrates or ammonia are taken up by the roots of the plants, and used for the production of organic nitrogenous bodies.

Miscellaneous Nitrogenous Substances.—Other nitrogenous substances found in plants are alkaloids, lecithin, chlorophyll, etc.

Alkaloids are substances of poisonous or medicinal character. Since they are bases, they unite with acids to form salts. Alkaloids are not found to any extent in ordinary agricultural products.

Lupine seeds contain from 0.02 to 0.65 per cent. alkaloids, according to the variety. The principal alkaloid is called lupinin. The seeds are so bitter that, without special preparation, they are not eaten by animals.

Tobacco contains 0.61 to 6.44 per cent. alkaloids, the chief being nicotine. In the pure condition it is very poisonous.

Caffeine is an alkaloid found in coffee and tea, to which they owe a portion of their properties.

Chlorophyll contains nitrogen, and so is included in protein.

Nitrogen-Free Extract.[1]—This term is used for the reason that the material is soluble in acids and alcohols, and is free from nitrogen. The nitrogen-free extract of seeds, and of many concentrated feeds consists largely of sugars, starches, and similar substances, which are easily digested and of high value to animals. But the nitrogen-free extract of hays, straws, and fodders con-

[1] See Tollens, Exp. Sta. Record 8, p. 641.

tains only relatively small quantities[1] of sugars and starches, and large amounts of less easily digested material.

The nitrogen-free extract makes up the largest part of most agricultural plants. In many instances it is as much as the sum of all the other constituents. The percentages in the dry matter of certain plants are given in the following table:

NITROGEN-FREE EXTRACT. (IN DRY MATTER.)

	Per cent.
Corn fodder	60.6
Timothy hay	52.8
Red clover	45.8
Cowpea vines	43.6
Potatoes	82.2
Corn	77.4
Wheat	80.4
Cowpeas	65.5
Soja bean	32.2

The nitrogen-free extract may contain sugars, starches, pentosans, hemi-celluloses, gums, vegetable acids, and miscellaneous bodies. It is composed to a large extent of carbohydrates.

Carbohydrates are compounds containing carbon, united with hydrogen and oxygen in the proportion to form water. Chemically, they are related to alcohols and aldehydes or ketones. The general formula of carbohydrates is $Cm(H_2O)n$. Glucose, $C_6H_{12}O_6$, starch $C_6H_{10}O_5$, and cane sugar (sucrose) $C_{12}H_{22}O_{11}$, are examples. Some carbohydrates are soluble in water and have a sweet taste, others are insoluble and tasteless. Some are easily acted upon by chemical reagents, while others, (particularly cellulose) are very resistant. All carbohydrates, however, may, by appropriate means, be converted into simple sugars.

It is not correct to use the term "carbohydrates" to signify the nitrogen-free extract. The nitrogen-free extract consists partly of substances other than carbohydrates. Crude fiber also contains cellulose, which is a carbohydrate.

Sugars.—The sugars are carbohydrates which are soluble in water, and, as a general rule, have a sweet taste. Cane sugar,

[1] Frear, Report Pennsylvania Station, 1903-4.

which is prepared from sugar cane or sugar beets, is the most common sugar. Sugars are divided into two groups: the simple sugars, or monosaccharides, represented by glucose, and the complex sugars, or polysaccharides, represented by cane sugar or sucrose. The complex sugars can be split up into one or more kinds of simple sugars. The sugars can all be crystallized, but in some cases crystallization is difficult.

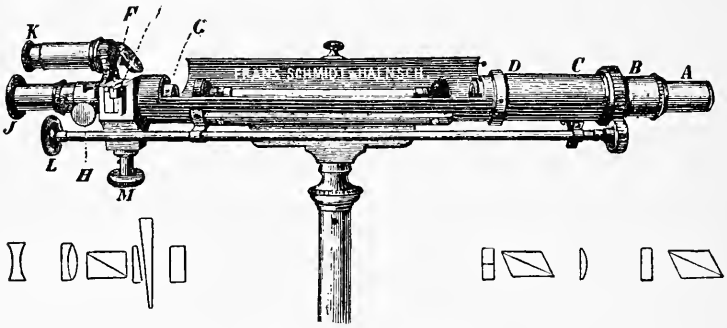


Fig. 80.—A polariscope.

Sugars are acted upon by acids and alkalies, forming various products, some of which are brown in color. Boiled with concentrated hydrochloric acid, cane sugar gives a black precipitate called *humic acid,* the name being given chiefly on account of its black color.

Optical Properties of Sugars.—If a ray of light is passed through a crystal of Iceland spar, it is split up into two rays, having peculiar properties, and called polarized light. If a ray of this polarized light falls upon another parallel crystal, in one position no light will pass through; if the crystal is rotated at an angle of 45°, all the light goes through, while in intermediate positions only a part is transmitted.

If the two crystals referred to above are placed so that all the light passes through, and a solution of sugar then placed between them, the polarized light will no longer all go through the second prism, but the prism must be rotated to a certain angle before the light will all pass through. The sugar has twisted the ray of

polarized light, or as it is termed, it has rotated the plane of polarization. The degree of rotation depends on the kind of sugar, the strength of the solution, the length of the column, and the temperature.

A *polariscope*[1] consists essentially of two Nicol prisms of Iceland spar properly mounted, between which the substance is placed, having lenses for suitable management of the light and the image. In order to measure the rotation, either the second crystal (called the analyzer) may be rotated, and the angle of rotation read, or the rotation may be compensated by a quartz wedge, which is likewise read on a graduated scale. Several arrangements are made in order that the reading may be accurate. In one type of instrument, the circular ray of polarized light is split into two half-discs, so that if the crystal or quartz wedge is moved slightly to the right, one-half of the image becomes dark, and if it is moved slightly to the left, the other half becomes dark. The intermediate position, at which both sides are of equal brightness, is the one at which the reading is taken. The instrument can be adjusted so that only a very slight change throws the shadow on the one side or the other.

The polariscope affords a very rapid and accurate method for estimating sugar, especially cane sugar, and it is used extensively in the analysis of sugar, sugar cane, sugar beets, and in the control of the processes of manufacture of sugar from cane or beets.

Reducing Power.—When simple sugars and certain compound sugars are boiled with copper salts in alkaline solution, the copper is reduced to cuprous oxide (Cu_2O), and may be collected and weighed as such, or as metallic copper. This property is used for the detection of sugars, and also for their quantitative estimation. The amount of sugar solution required to reduce a given amount of copper may be used to measure the amount of sugar. The amount of copper reduced depends upon the nature of the sugar, the volume of the solution, the time of heating, the composition of the copper solution, and other details of the analytical process.

[1] See Wileys Principles and Practice of Agr. Chem Anal., Vol. III.

Tables have been prepared showing the amounts of copper which were found by experiments to be reduced by given sugars under fixed conditions; these tables can be used in the estimation of sugars under the same conditions, but the details of the method used in preparing the tables must be followed carefully.

The copper solutions used ordinarily are Fehling's solution, containing fixed quantities of copper sulphate, sodium potassium tartrate, and sodium hydroxide; and Allihn's solution, containing certain amounts of copper sulphate, sodium potassium tartrate and potassium hydroxide. Other solutions are used. Different sugars require different quantities of copper under the same conditions. For example, the same amount of copper will be reduced from Sachsse's solution by the following amounts of sugars:

Fructose 213 mg.
Maltose 491 mg.
Lactose 387 mg.

Fermentation.—Under suitable conditions, yeast converts certain sugars into alcohol and carbon dioxide according to the following reaction:

$$C_6H_{12}O_6 = 2C_2H_6O + 2CO_2.$$

Yeast is a plant which grows in the solution, and develops an enzyme which changes the sugar as described. Like all plants, yeast must have nitrogenous food, also phosphoric acid, potash, and lime. Yeast will not grow well in pure sugar. An *enzyme* is a substance which causes a chemical change, without itself being changed in the reaction.

The simple hexoses are easily fermented. Some of the compound hexose sugars ferment readily, while others must first be split up into the simple hexoses. Pentosans do not undergo the alcoholic fermentation.

There are other kinds of fermentation, probably the most important being the acetic fermentation, in which alcohol is converted into acetic acid (vinegar), and the lactic acid fermentation, in which sugar is converted into lactic acid. This takes place in the souring of milk.

Fermentation is important in the manufacture of cider from apple juice; wine from grape juices; and alcoholic beverages and alcohol from materials containing starch or sugar, such as potatoes, corn, rye, barley, etc.

Classes of Simple Sugars.—Four groups of simple sugars are known to chemists, though only two of these are of agricultural importance. The groups are: (1) the trioses, containing three carbon atoms in the molecule $C_3H_6O_3$; (2) the tetroses, containing four carbon atoms, $C_4H_8O_4$; (3) the pentoses, containing five carbon atoms; and (4) the hexoses, containing six. All the natural carbohydrates are related to either the pentoses or the hexoses. The principal simple sugars are xylose and arabinose, which are pentoses; and glucose, fructose, mannose, and galactose, which are hexose sugars.

Each of these sugars exists in three modifications, namely, one which rotates polarized light to the right, one which rotates polarized light to the left, and one which does not rotate it, and is inactive. Thus we have d-glucose, l-glucose and i-glucose, dextro-, laevo-, and inactive glucose. Although many of these sugars are known, as a rule only one modification of each sugar is of natural occurrence. Thus natural glucose is dextro-rotatory. and was formerly called dextrose for this reason, and ordinary fructose is laevo-rotatory, and was called levulose.

Pentose Sugars, $C_5H_{10}O_5$.—The pentose sugars occur to a very limited extent, if at all, in nature. They are of agricultural importance on account of their relation to the pentosans, which are found in large quantities in agricultural products.

When distilled with strong hydrochloric acid, the pentoses and pentosans are converted into furfural,[1] which distils over with the acid:

$$\underset{\text{Pentose}}{C_5H_{10}O_5} = \underset{\text{Furfural}}{C_5H_4O_2} + 3H_2O$$

The furfural can be precipitated with a solution of phloroglucinol, the product being furfural phloroglucid. The precipitate is filtered off, dried, and weighed. The quantity of furfural

[1] Landw. Versuchs-stat., 42, p. 381.

yielded by the different pentose sugars and pentosans under the conditions of the work have been determined by experiments.

Stoklosa found considerable quantities of water-soluble pentosans in sugar beet seed, and DeChalmot found small quantities in the leaves and bark of a number of plants. But pentose sugars have not been separated as such from plants, but are prepared by the hydrolysis of certain pentosans. The pentoses do not ferment with yeast.

Arabinose, $C_5H_{10}O_5 = CH_2OH(CHO)_3CHO$, has been prepared from the pentosans found in lupines, soja beans, rye bran, wheat bran, plums, and cherry gum. It is easily prepared by boiling cherry gum with 2 per cent. sulphuric acid. It crystallizes beautifully, and has a sweet taste, but not as sweet as sucrose.

Xylose, $C_5H_{10}O_5$, has been prepared from beech wood, jute, fir wood, cherry wood, laurel wood, wheat straw, corn cobs, oat straw, rye straw, corn bran, apples, etc. It crystallizes in prisms.

Rhamnose, $C_6H_{12}O_5 = CH_3(CHOH)_4CHO$, is methyl pentose, which yields methyl furfural by distillation with hydrochloric acid. It is obtained from certain glucosides, and crystallizes in beautiful, sweet crystals.

Hexose Sugars, $C_6H_{12}O_6$.—The two hexose sugars of common occurrence are fructose and glucose. They occur, in equal quantity, in sweet fruits, flowers, certain vegetables. The other hexoses are formed by the hydrolysis of certain carbohydrates. All the hexoses are fermented by yeast.

d-Glucose, $C_6H_{10}O_5$, or grape sugar, occurs in grapes, sweet fruits, tomatoes, seeds, roots, leaves, flowers, honey, etc. Together with fructose, it is formed by the hydrolysis of cane sugar. It is also formed by the hydrolysis of starch, and is the chief ingredient of many syrups. Nitric acid oxidizes it to saccharic acid, and glucose may be detected by means of this reaction. It is also detected through its optical properties. Glucose is a white crystalline substance, which is not so sweet as cane sugar. It is easily soluble in water and alcohol. It undergoes fermentation of various kinds readily. Glucose is produced commercially by the

action of dilute acids upon starch. The acid splits up the starch, and causes it to unite with water

$$(C_6H_{10}O_5) + X\ H_2O = C_6H_{12}O_6.$$
Starch. Glucose.

The thick syrup formed after the acid is neutralized and the solution evaporated is called glucose syrup or corn syrup. It does not consist of pure glucose. If a solid mass is produced, it is called grape sugar.

Fructose, $C_6H_{10}O_5$, accompanies glucose in most fruits and vegetables. It is difficult to crystallize. It is obtained by hydrolysis of inulin. So-called invert sugar is a mixture of equal quantities glucose and fructose, and is formed by the hydrolysis of sucrose. Honey is a natural invert sugar, dissolved in water, with small quantities of impurities. While glucose may be separated from invert sugar comparatively easily, it is not easy to separate fructose on account of its difficult crystallizability.

Mannose, $C_6H_{10}O_5$, has not been found in nature. It has been prepared by the hydrolysis of vegetable ivory, the seeds of palms and lilies, coffee beans, and gum arabic, etc.

Galactose, $C_6H_{10}O_5$, has not been found as such in nature. It is a product of the hydrolysis of milk sugar, and of carbohydrates found in seeds of lupines, beans, soja beans, peas, vetch, cress, young clover, lupine, and lucerne plants, in gum arabic, fruits of pears, etc. Nitric acid oxidizes it to *mucic acid,* which is almost insoluble in water. A method for its estimation is based upon this fact.

Compound Sugars.—The most important compound sugars are cane sugar, milk sugar, raffinose, maltose, and stachyose. They are derived exclusively from hexoses.

Name and Formula	Hydrolized to	Action towards Fehling solution
Cane sugar, $C_{12}H_{22}O_{11}$	Glucose and fructose	No action
Milk sugar, $C_{12}H_{22}O_{11}$	Glucose, galactose	Reduces
Maltose, $C_{12}H_{22}O_{11}$	Glucose	Reduces
Raffinose, $C_{18}H_{22}O_{16}$	Glucose, fructose, galactose	No action
Stachyose, $C_{18}H_{32}O_{16}$	Glucose, fructose, glucose	No action

Like the monosacchosides, the polysaccharides are neutral, sweet, colorless compounds, easily soluble in water, and they are readily crystallizable. They are easily converted into monosaccharides by the action of warm dilute acids, or certain unorganized ferments. The ease with which this action takes place depends upon the nature of the sugar; simply warming for a short time with a dilute acid is sufficient to split cane sugar (sucrose) into glucose and fructose, while maltose requires to be boiled for some hours with the acid for complete inversion.

Sucrose, $C_{11}H_{22}O_{11}$, is prepared from sugar cane, sugar beets, and maple sap. The impurities which accompany the sugar are different when prepared from these three sources, but no differences can be detected in the sugar when it has been thoroughly purified.

Sucrose is widely distributed. The juice of sugar cane, sweet sorghums, and sugar beets contains 10 to 20 per cent. Peanuts contain 4-6 per cent., sweet potatoes 1-3 per cent., the seeds of beans, peas, vetch, soja beans, hemp, and sunflower seeds contain 4-6 per cent. Some fruits contain 5 per cent. or more. Green corn, before the ears are formed, is quite rich in sucrose.

Sucrose crystallizes in regular crystals belonging to the monoclinc system. It is easily soluble in water and has a high dextro-rotatory power. It melts at 160° C. and solidifies on cooling to an amorphorous glassy mass. A high temperature converts it into a substance known as *caramel,* which is used for coloring some food materials. A still higher temperature carbonizes it with evolution of gases and vapors.

Sucrose does not reduce Fehling's solution, but can easily be converted into invert sugar, which has reducing power. This is a method for its estimation. The polariscope is also used for the estimation of sugar. The inversion of sugar takes places in the ripening of some fruits, the curing of fodders, and in the cooking and preparation of human foods.

Manufacture of Sugar.—The processes of manufacture from sugar cane and sugar beets vary somewhat in details. The beets are first sliced, and the sugar extracted with warm water or sugar

solution, in a series of vessels. The water comes in contact first with beet slices nearly exhausted of sugar, then it is brought in contact with slices richer in sugar, and finally passes through the vessel containing fresh beet slices. This system exhausts the beet, and at the same time secures a comparatively strong solution of sugar.

The sugar juice is acid. It is treated with lime to neutralize the acid, which would otherwise invert the cane sugar when the juice is heated and decrease the yield. The lime also precipitates a quantity of impurities. The lime which goes into solution is next precipitated with carbon doxide and the solution is finally neutralized and bleached with sulphur dioxide.

The sugar solution is next evaporated until the sugar is ready to crystallize. Since inversion would take place at the temperature required for rapid evaporation in the open air, and since there would also be danger of burning, the evaporation is carried on in a vacuum, in which the solution boils at a comparatively low temperature. The solution is drawn off when the sugar is ready to crystallize, allowed to cool, and the mother liquor extracted from the crystals in a centrifuge by centrifugal force.

Sugar is prepared from sugar cane in essentially the same way. The juice is squeezed out by passing the cane between heavy rollers, instead of being extracted by diffusion. The pressed cane is termed *bagasse*. The sugar is sent to a refinery for further purification.

Syrup is prepared from sorghum, sugar cane, or maple sap by evaporating the juice, usually in open kettles, with or without previous purification with lime and sulphur.

Milk Sugar, $C_{12}H_{22}O_{11}$, (lactose) is not found in plants, but occurs in the milk of animals to the extent of 3 to 6 per cent. It remains in solution when the casein and fat of milk have been separated (as occurs in the manufacture of cheese), and may be prepared by evaporating the liquid and recrystallization of the product. It appears as hard white crystals with a slightly sweetish taste. It is not as easily soluble in water as cane sugar. It is hydrolyzed to d-galactose and d-glucose.

Milk sugar reduces Fehling's solution and does not ferment until inverted.

Maltose, $C_{12}H_{22}O_{11}$, is formed from starch by the action of diastase, a ferment found in sprouting barley and other seeds, and is important in the manufacture of beer, alcohol, and alcoholic beverages from starchy materials. It forms fine, white needles, is easily soluble in water, and is hydrolyzed to glucose.

Raffinose occurs in small quantities in sugar beets, and in barley, and in considerable quantities in cotton seed. It crystallizes as needles or prisms, is easily soluble in water and methyl alcohol, but is scarcely soluble in ordinary alcohol. It does not act upon Fehling's solution. It is first broken down by hydrolysis into two reducing sugars, fructose and melibiose; the latter is then split up into glucose and galactose.

Stachyose occurs in the tubers of stachys tuberifera. It is hydrolyzed to galactose, fructose, and glucose.

Starch, $C_6H_{10}O_5$.—This is found in the most different organs of plants in the form of granules having an organized structure.

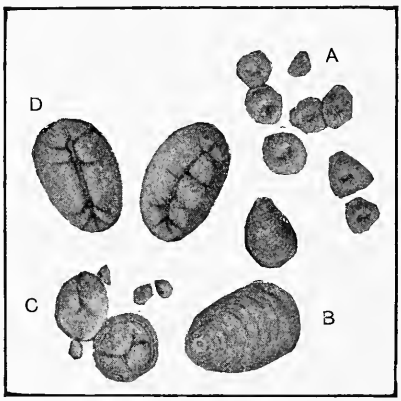


Fig. 81.—Starch granules, (A) corn, (B) potato, (C) wheat, (D) bean. After Wiley.

It is one of the first products of the assimilation of carbon dioxide, and can be easily detected in the chlorophyll granules of the leaf. It is transferred from the leaf in a soluble form, and

used for the construction of other plant substance, or stored up as reserve material as such. Starch is thus found abundantly in many seeds, roots, and tubers, the parts of the plant concerned with new growth.

The starch granules vary in size and structure according to their origin. Potato starch appears mostly as oval granules with an average diameter of 0.07 mm., but it contains large granules. Wheat starch contains circular granules of two sizes, smaller than 0.007 mm. diameter and larger than 0.2 mm. with few granules of intermediate size. The structure of the granules, and their behavior towards polarized light is also different, so that one familiar with their appearance can easily identify starches of different origin by means of a microscopic examination.

The elementary composition of starch is represented by the formula $C_6H_{10}O_5$, but its molecular formula is not yet known. Many chemists hold that the starch molecule may contain more than 100 carbon atoms.

Properties of Starch.—Air-dry starch contains 10 to 20 per cent. water. By carefully drying at 102-110° C., it may be obtained water-free. In cold water it is insoluble. With hot water the granules swell, break, and form starch paste, a pasty solution, from which a clear filtrate can be secured. By treating starch for several days with cold dilute mineral acids, it may be changed into "soluble starch," which dissolves in hot water without formation of a paste. Starch is tasteless and colorless.

Starch is especially characterized by the blue color it gives with iodine. This is a very delicate test for both starch and iodine. Starch is used as an indicator with volumetric solutions containing iodine.

When heated with dilute mineral acids under proper conditions, starch is converted almost quantitatively into glucose. As we have already seen, this property is utilized in the manufacture of glucose and glucose syrup from starch.

Under other conditions, dilute acids change starch into a gummy substance termed "dextrin." This occurs in some mucilages made from starch.

When heated to a temperature above 120° C., starch is changed to dextrin. This takes place in the browning of flour, preparation of toast, and some other processes of cooking.

When starch paste is treated with malt (this is best done at a temperature of about 65°), it is converted into maltose and dextrin, and goes into a solution, which may be fermented. Advantage is taken of this property in the manufacture of alcohol or alcoholic beverages from materials containing starch, such as corn, rye, barley, etc. The grain is ground, heated with water, treated with malt, and to the aqueous solution yeast is added to cause fermentation. If alcohol or whiskey is desired, the fermented material is distilled. The residue from the treatment with malt is dried and used for cattle food (brewers' grains), or it may be fed without drying.

Malt is partly sprouted barley, the sprouts being rubbed off. It contains an enzyme known as diastase, which acts upon starch as stated above.

Manufacture of Starch.—Starch is made from potatoes, corn, arrow-root, cassava, and other materials rich in it. The preparation of starch from potatoes is a simple mechanical operation. The potatoes are washed and grated to a pulp to break the cell walls. The starch is washed out of the pulped mass on sieves. It is allowed to settle and dry. With some other materials such as wheat and rice, the proteids which accompany the starch must be brought into solution by fermentation or by means of caustic soda.

Inulin, $C_6H_{10}O_5$, is found dissolved, in a pasty condition in many plants of the Compositae family, and in these plants plays the part that starch does in most others. It is obtained from the dahlia tubers. It is a white powder, composed of small crystals, easily soluble in warm water, being slowly precipitated on cooling, but readily by alcohol. It is not colored by iodine, hardly affected by diastase, and is much more easily hydrolized by dilute acids than starch. Since it yields only fructose, it is used for the preparation of pure fructose.

Glycogen, $C_6H_{10}O_5$, is a starch-like carbohydrate found in

animals. From 0.6 to 0.7 per cent. is found in the muscles, but it disappears while the animal is at hard work or starving. It is contained in quantity in the liver, and is the reserve material formed from the excess of carbohydrates for the furnishing of sugar to the blood.

Gums.—Gums are found in many vegetable materials. They often exude from cut places. Both hexoses and pentoses are formed by the hydrolysis of gums. Some of the gums are the best materials for the preparation of the pentose sugars.

The following are some gums and the sugars they yield on hydrolysis:

Gum arabic yields galactose and arabinose.

Wood gum, extracted from wood by alkalies.

Cherry gum yields arabinose.

Peach gum yields galactose and arabinose.

Barley gum yields galactose and xylose.

Galactan yields galactose and other sugars, and is found in leguminous plants.

Pectins.—These are substances found in fruits and some fleshy roots. They are soluble in water, and precipitated as a jelly-like mass by alcohol. When boiled sufficiently, they jelly on cooling. If boiled too long, they will not jell. Pectins appear to be closely related to the carbohydrates, or belong to them. They are found in apples, pears, quince, cranberries, beets, turnips, etc.

Cellulose, $C_6H_{10}O_5$.—Cellulose is the chief constituent of the cell walls of plants. It is insoluble in warm dilute acids or alkalies. In young parts of plants, the cell walls are composed of almost pure cellulose. In older organs the cellulose is interpenetrated with "incrusting material." Cellulose is found abundantly in wood tissue and woody tissue of all kinds. Cotton is almost pure cellulose. Flax and hemp are composed largely of cellulose. It may be prepared by treating the material successively with ether, boiling dilute acid, boiling dilute alkali, and then with cold dilute nitric acid and potassium chlorate to remove the incrusting material. The residue consists of cellulose. Cellulose is a colorless insoluble material. Its molecular weight is unknown

Cellulose may be dissolved in a solution of copper oxide in ammonia. It also dissolves in concentrated sulphuric acid. If the solution is immediately diluted with water, a jelly-like mass is precipitated. If digested for some time with the acid, and the solution then diluted and boiled for some time, sugar is produced. The product is glucose from cotton and many other celluloses, but d-mannose is secured from some other celluloses, such as those from the coffee bean and sesame seed. The function of cellulose in plants is to form the structure of plant cells. In seeds it acts as a reserve material. Digested cellulose appears to be equal in value to other carbohydrates. Cellulose contains 44.4 per cent. carbon.

Lignin.—This is the term applied to the incrusting substances which accompanies the cellulose in wood and woody cells. Crude fiber is largely composed of this mixture or, perhaps compounded of cellulose and lignins. The chemical nature of the lignins is not clearly known. They do not appear to belong to the group of carbohydrates, but contain 55-60 per cent. carbon. Cutin contains 68-70 per cent. carbon.

The quantity of lignins in the plant increases with the age of the plant tissue. Young woody tissue may contain little lignin, while old woody tissue may be composed largely of it. The greater the quantity of lignin in the material, the lower its value for feeding purposes.

Hemicelluloses.—This term has been proposed for the carbohydrates of the cell walls which are insoluble in water, but, unlike cellulose, are brought in solution by dilute acids or alkalies. Such carbohydrates are of extensive occurrence. The sugars produced by their hydrolysis are both pentoses and hexoses. Hydrated celluloses, formed by the union of cellulose with water, are largely dissolved by acids or alkalies, and hence would be classed with the hemicelluloses.

Pentosans.—Pentosans may be defined as carbohydrates insoluble in water, which yield pentose sugars on hydrolysis. The reaction resulting in the formation of furfural when pentosans are boiled with strong acids, is used for their estimation. The

pentosans are accompanied with a substance[1] which yields a furfural-like product, but which product decomposes on standing and does not distil with the furfural a second time. Pentosans occur in most plant materials, and are particularly abundant in hays and straws. The pentosans are chiefly gums, pectins, and hemicelluloses, though a certain quantity is always found in the crude fiber.

Digested pentosans appear to be of considerable value to the animal. Although it is possible that they have the same value as starch, when once digested, yet the digested portion of feeding stuffs rich in pentosans has a decidedly lower value for productive purposes than that of starchy materials. This appears to be due in part to the labor of chewing the crude fiber of such materials, but the labor of chewing does not account for the entire deficit.

The following table shows the relative occurrence of these classes of substances in different materials.[2]

NITROGEN-FREE EXTRACT OF SOME FEEDING STUFFS.

	Per cent. on dry matter			
	Simple sugars	Compound sugars	Pentosans	Residues
Timothy hay	4.97	3.33	19.71	16.88
Crabgrass	1.42	0.47	4.35	21.40
Cowpea meal	—	5.66	6.83	52.20
Corn	1.76	0.11	—	—
Green rape	5.22	1.81	9.57	29.81
Cottonseed meal	0.22	10.73	6.76	5.46

Crude Fiber.[3]—The organic residue left after extraction of plant substance with ether and boiling it successively with 1¼ per cent. acid and alkali, is termed crude fiber. The process is arbitrary, and the object in view when it was devised was to secure a product as free as possible from nitrogen.

[1] N. C. Bulletin, No. 178.

[2] Fraps, Jour. Am. Chem. Soc., 1900, p. 543.

[3] See Tollens, Exp. Sta. Record 8, p. 649.

Crude fiber consists of cellulose, lignin, cutin, pentosans, and other substances. Digested crude fiber appears to be equally as good as starch, but the labor of chewing materials containing much crude fiber, largely counteracts the value of the food.

Seeds and tubers contain little crude fiber. Hay, straw, chaff, and woody materials in general may contain considerable quantities. For the crude fiber content of some materials, see the tables of analyses.

About 20 per cent. of the pentosans of hays and straws is in the crude fiber, making up 10 to 15 per cent. of the crude fiber.

	Total pentosan	Pentosan in crude fiber
Timothy hay	24.86	5.15
Crabgrass hay	26.25	4.35
Cottonseed hulls	20.00	5.36

Organic Acids.—Organic acids are found in plants and plant products, though often in very small quantities. They may be present in the free state, but are usually present as salts of lime or potash. In green plants the acids are found mainly in solution in the sap; later on they are deposited into the cell tissues.

The quantity of organic acids in ordinary agricultural plants is very small. Appreciable amounts are found in fruits and some vegetables. *Tartaric* acid occurs in appreciable amounts in grapes, and is deposited as potassium acid tartrate in wine. Small amounts are found in pineapples, cucumbers, and tomatoes. *Malic* acid occurs in apples, from which it gets its name, but is widely distributed, occurring in a number of fruits and vegetables. *Oxalic* acid and *succinic* acid are found in many plants.

Citric acid is present in lemons and limes, and in small amounts in pears, beans, cherries, and other fruits. *Tannic acid* is not present in food plants to appreciable extent, though it is found in tea and coffee. It is used for tanning leather. Some plants are grown for the tannic acid they contain.

Lactic acid occurs in silage and sour milk.

The organic acids have little food value, but affect the palat-

ability of the food, and perhaps exert a favorable influence upon digestion by stimulating the secretion and flow of the digestive juices.

Essential Oils.—The characteristic flavor and odor of many plant products are due to volatile compounds known as essential oils. Turpentine, peppermint oil, oil of roses, and oil of lemon are examples of essential oils. Spices, flavoring extracts, condiments and appetizers in general, flowers, and certain fruits are characterized for the most part by the presence of essential oils. Hays owe a portion of their odor and flavor to essential oils. Rape, turnips, cabbage, and parsley contain essential oils. Some of the essential oils impart palatability to the food, and stimulate the secretion and flow of the digestive juices. While of little or no value for the production of muscle or energy, they aid the appetite of the animal.

Certain feeds containing essential oils are undesirable for milch cows, as they impart a disagreeable flavor to the milk. Garlic, wild onions, and rape are examples of these.

Organic Phosphorus Compounds.—Plants also contain organic phosphorus compounds, chief among which is phytin,[1] which may be decomposed into inosite and phosphoric acid. This substance is found especially in wheat bran, rice bran, and cottonseed meal. Other organic phosphorus compounds are present.

Heat Value.—The energy of a feed or nutrient is measured by the heat which it produces when burned. The unit of heat is the calorie, written c., which is the amount of heat required to raise the temperature of 1 gram water 1° Centigrade. The large calorie (C) is 1,000 c, and the therm (T) is 1,000 C. Several kinds of calorimeters are used. In the bomb calorimeter, the material is placed in a platinum capsule in an iron vessel, lined with platinum or enamel. The bomb is filled with oxygen under high pressure, and placed in a vessel of water with a stirrer, and thermometer, and properly insulated to decrease heat changes. The material is ignited by means of an electric current which heats a small piece of iron wire, and the rise in temperature of the water is ascertained. Knowing the amount of heat required to

[1] N. Y. (Geneva) Bull. 250; Texas Bull. 156.

heat the apparatus, the quantity of water, the rise in temperature, and the loss of heat by radiation, the amount of heat produced by the known weight of substance may be ascertained. Urine is

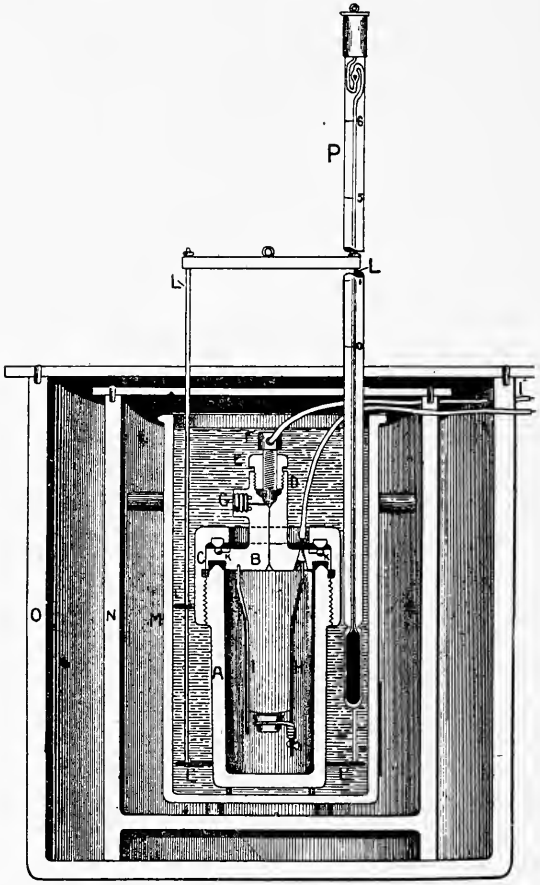


Fig. 82.—Calorimeter (Atwater and Hempel) in which the substance is burned in compressed oxygen.

either evaporated in a vacuum directly, or absorbed in paper of known heat value, and then dried. Heat measurements are made very often in investigations of animal nutrition.[1]

[1] For discussion of heat values of nutrients, see Stohmann, Exp. Sta. Record No. 6, p. 590.

CHAPTER XVIII.

COMPOSITION OF PLANTS AND FEEDS.

Feeding stuffs are divided into two great groups—concentrates and roughages. A concentrate, or concentrated feeding stuff, consists of seeds, and various milling by-products. A concentrate is rich in protein or in nitrogen-free extract and contains comparatively small amounts of crude fiber. As a general rule, the crude fiber of a concentrated feed does not exceed 10 per cent., though there are exceptions; crushed cottonseed cake, for example, contains about 27 per cent. Examples of concentrates are corn, wheat, rice bran, cottonseed meal, gluten meal, wheat bran, etc.

A roughage is a feed containing relatively high percentages of crude fiber and much smaller amounts of nitrogen-free extract and protein. Further, the constituents of the nitrogen-free extract are less digestible and less valuable to the animal than those of concentrates.

Seeds.—The seed contains an embryo plant with sufficient plant food and organic matter to give the young plant a good start in life. Seeds of agricultural importance may be divided into three classes:

(*a*) *Starchy Seeds.*—Seeds of the cereals belong to this group.

(*b*) *Oily Seeds.*—Seeds of cotton, flax, hemp, sunflower, mustard, etc., belong in this group. Oil is manufactured from them.

(*c*) *Seeds Rich in Protein.*—Seeds of peas, beans, and other leguminous crops belong in this group.

Other classes of seeds are known, but they are not of great agricultural importance.

Germination.—In germination, the reserve material in the seed is converted into soluble forms, conveyed into the growing plant, and formed into new material. The chemistry of this change depends to some extent upon conditions. The proteids are converted into asparagin and other amido bodies, and the fat is oxidized and changed to soluble materials, which are used by the

plant. The reserve carbohydrates undergo changes similar to the fat. In some seeds, as in barley, ferments are formed which change starch into sugar.

The change in composition of seeds on sprouting may be studied by allowing a weighed quantity of seed to sprout in the dark, and determining the constituents of the original seed, and of the sprouted seed. The sprouting must take place in the dark, since when light is present carbon dioxide is assimilated and masks the change.

Composition of Plants at Different States of Growth.—Plants do not have the same composition at different stages of growth. The plant increases in weight up to maturity. In the earlier part of the life of the plant, nitrogenous material is taken up more rapidly. Before the formation of fruit, the reserve material produced is stored up in leaves, stem, roots, or tubers. At the time of fruiting, this reserve passes into the seed. During the later stages of plant growth, lignification of the tissues takes place. That is to say, the cellular material becomes penetrated with lignin and the stems, etc., become more woody and difficult to digest.

The composition of plants at different stages of growth may be studied in two ways.

The first method consists in selecting and analyzing average specimens of the plant at the desired periods of growth. This method of experiment shows the change in the individual plant.

The second method consists in harvesting definite areas of the same field when the field has reached the average condition desired and subjecting samples to analysis. This method represents the production of the *field* at different stages of growth. The plants harvested are not all in the same condition of growth. This method is better suited for small plants and grasses than the first method. Both methods are open to error, as there may be differences in the soil or in the individual development of different plants.

The general results of these experiments are as follows:

The water in the green plant decreases with the age of the

plant. In order to eliminate the effect of this variation, the percentages of other constituents of the plant should be calculated to percentages of the water-free substance, or *dry matter* of the plant. The statements below refer to the composition of the dry matter.

The percentage of ash usually decreases with the age of the plant. That is, the production of organic matter takes place more rapidly than the withdrawal of ash material from the soil.

The percentage of *protein* decreases decidedly. In some cases the percentages when the seed are nearly ripe are only about half those at the beginning of growth. The protein, however, consists largely of amides or amido compounds in the early stages of the plant's life, and these amides have little or no value for the pro-

Composition of Some Plants at Different Stages of Growth.

	Water	Water-free				
		Ash	Protein	Fiber	Nitrogen-free extract	Fat
Corn						
July 22	88.61	8.5	17.2	26.0	45.1	3.2
July 29	85.76	8.0	14.4	27.3	47.6	2.7
August 5, tasseled	84.64	5.9	11.8	26.4	53.6	2.3
August 13	82.08	5.7	11.2	24.1	56.9	2.1
August 27	81.15	4.7	8.9	24.3	60.3	1.8
September 3	76.81	4.2	9.2	20.9	63.1	2.6
Timothy						
June 23, nearly headed	78.70	7.5	11.0	28.7	49.0	3.8
July 3, full bloom	71.92	6.1	8.3	33.3	49.3	3.0
July 14, out of bloom	65.70	5.2	5.7	34.7	51.7	2.7
July 30, nearly ripe	63.27	5.0	5.5	37.1	50.2	2.2
Kentucky Blue Grass						
April 28, 3 to 6 inches	68.05	11.5	18.0	22.2	42.7	5.6
May 8, 8 inches	66.71	10.7	13.5	22.7	48.9	4.2
May 18, panicles spreading	63.3	8.7	11.1	24.4	51.9	3.9
May 28, early bloom	62.91	8.5	9.7	29.1	50.5	2.2
June 7, after bloom	61.24	8.7	7.9	29.9	51.8	2.7
July 5, in seed	51.67	10.0	7.9	30.5	48.5	3.1
Red Clover						
Just before bloom	61.21	8.3	14.3	27.8	47.9	1.7
Full bloom	47.13	7.7	13.5	27.8	48.6	2.4

duction of flesh. As the plants approach maturity, the percentages of non-proteid nitrogen decreases.

The fat is irregular, though it shows a tendency to decrease. The crude fiber increases with most plants. Indian corn is an exception, since the production of a large quantity of starchy seed decreases the percentage of fiber. The nitrogen-free extract usually increases, though the changes are somewhat irregular. The digestibility decreases.

The total quantity of dry matter per acre appears to increase during the entire period of growth. In the latter stages of maturity of the plant, the increase is largely made up of crude fiber.

Some analyses of plants at different stages of growth are shown in the table.[1]

Time of Harvest.—The best time to harvest depends on the kind of plant and the purpose for which it is grown, as well as on the weather of the harvesting period.

Suppose hay is grown for market. The object then is to secure the largest possible quantity of hay of the highest market value. A large quantity of low grade hay may, or may not, be more profitable than a smaller quantity of high grade hay.

Suppose hay is grown for feed. The object is then to get the largest possible amount of digestible nutrients per acre. The best period of harvest for this purpose is when the plant is in full bloom.

Suppose the clover or grass is grown for seed. Then the object is to produce the most seed of the best quality. The seed must be well matured, but at the same time the harvest must not be so late that any considerable quantity is lost by shattering.

Other Factors which Influence Composition.—Other factors which influence the composition of crops are the seed, the soil, climate, and method of preparation or preservation.

The composition and individuality of the seed influence the composition and size of the plant. In many cases, the heavier

[1] Compiled from Bulletin 11, Office Exp. Station, U. S. Dept. Agr.

the seed, the more vigorous the young plant. The larger seed, of course, contain more reserve material and plant food.

Selection of seed from individuals of a desired type may affect the composition of the plant. Thus, at the Illinois Station, corn of high and low protein and high and low fat have been produced. By selecting seeds from beets containing high quantities of sugar, the sugar content of the sugar beet has been increased 8 to 10 per cent. It is not possible to improve all crops in this way.

The soil affects the composition of the crops to some extent. Foliage crops grown upon rich soils contain a larger percentage of nitrogen than those grown on soils poor in nitrogen. Leaves and stems are influenced to a greater extent than seed by the soil, because the seed are more constant in composition. Wheat and other grains show material differences in composition when grown upon different soils. Not all plants are affected by the composition of the soil. Lawes and Gilbert found that the use of nitrogenous and mineral manures for twenty years did not affect the nitrogenous content of wheat.

As the plant contains more nitrogen during early stages of growth, anything which cuts short the growing season will cause the crop to contain slightly more nitrogenous material. If the growth of the plant is checked at the time of seed formation, shrunken or immature seed may result. Such grain contains less starch and more nitrogenous compounds than those fully matured. Plants grown in arid or semi-arid regions may contain a higher percentage of nitrogen than in regions of more abundant rainfall. For instance, the nitrogen content of Texas cottonseed meal[1] is considerably greater in the western or semi-arid part of the state than in the eastern part.

Hay and Hay Making.—Hay is the dried and partly fermented leaves and stems of certain grasses and clovers. Some fermentation is requisite to develop the characteristic flavor and aroma. The method used for hay making depends on the character of the plant and the climate. A succulent plant and a moist climate demands more care than dryer plants and a dry climate. Some

[1] Texas Bulletin, 70.

plants, such as cowpeas, are difficult to cure on account of the large succulent vines, which remain moist after the leaves have become dry and so brittle that they break off. For a similar reason alfalfa also is difficult to cure . Often alfalfa hay consists entirely of stems.

The Arkansas Experiment Station found that young or vigorously growing vines of cowpeas very difficult to cure even under favorable weather conditions, while mature vines cured with little difficulty in favorable weather, and usually made good hay even after an exposure to rain and cloudiness from two to four days.

In hay making the plants are usually cut and allowed to lie exposed to the sun all day; then raked or piled into heaps more or less loose, for further curing, and finally piled into larger heaps, or taken to the barn. If the large heaps are formed while the material is too moist, excessive fermentation will take place, which in some cases has gone so far as set fire to the stack. In Wisconsin, Short found that by leaving hay out four days after cutting, during which time there was a rain, there was a loss of over 4½ per cent. dry matter and 3½ per cent. protein. Six weeks later nearly one-fourth of the dry matter and protein disappeared.

Emmerling left grass exposed for 18 days, during nine of which rain fell, with the results given in the following table:

PERCENTAGE LOSS OF INGREDIENTS OF HAY IN EXPOSURE TO RAIN.

	In cocks	In swaths
Dry matter	18.3	29.4
Fat	31.0	41.0
Crude protein	29.0	24.8
Digestible protein	19.8	38.8

Even without rain, when the process of drying is slow, a loss takes place due to the respiration of the living tissues, by which protein is decomposed or non-proteins oxidized. The loss has been as much as 12 per cent. dry matter in 10 days with young grass.

Silage.—Silage is a feeding-stuff preserved in a moist condition. It is made by placing the finely chopped material in an air tight receptable. More or less fermentation takes place,[1] which destroys sugar, produces acids, and causes the loss of ten or twelve per cent. substance. The acidity of the silage depends upon the conditions of preparation. If a silo is filled rapidly, the mass weighted down and the air excluded as much as possible, a slow fermentation takes place caused by bacteria, which results in a very acid product, termed sour silage. It may contain 0.6 to 1.6 per cent. acid. If the material is put in slowly and loosely, a preliminary rapid fermentation takes place which heats the mass, destroys the acid-forming bacteria, and excludes air. Fermentation then goes on more slowly, producing a sweet silage. Too high a temperature would produce bad results. Sweet silage is said to become moldy on exposure to the air, while acid silage is relatively resistant to decay. The changes are due to the living cell, and enzymes of the plant, as well as to bacteria.

The following experiment shows the effect of temperature on the silage. The volatile acid is chiefly acetic acid, the non-volatile is lactic.

Temperature of formation	Volatile acid Per cent.	Non-volatile acid. Per cent.
Below 32° C.	0.62 to 1.56	0.10 to 0.9
32 to 49° C.	0.38 to 1.19	0.31 to 0.23
56 to 70° C.	0.00 to 0.6	0.02

The fermentation also converts some of the proteid nitrogen into non-proteids, the action going so far as even to form a small quantity of ammonia.

A silo must be perfectly air-tight, or the loss resulting will be great; the walls must be rigid, the inner surface must be smooth and uniform, and it should dry out quickly and completely.

Losses in Silage Making.—The loss in a silo depends upon its construction, on the crop siloed, and on the amount of moisture present. The loss is much lessened by proper construction of the

[1] Bulletin 70, Connecticut Station.

silo. The amount of moisture present in the crop had the following effect in one experiment:

Moisture, per cent.	Loss, per cent.
71.67	8.63
74.61	10.01
80.66	16.66

An excess of moisture thus causes a greater loss. Water is sometimes added to crops siloed when they do not contain enough water to make good silage.

As regards the nature of the crop, King found the necessary loss for corn to be 5 to 10 per cent., and for clover 10 to 18 per cent. Corn well matured and in good condition for shocking, but with leaves still green, is in the proper stage for silage. Silage from immature fodder is more acid than that from more mature plants.

Feed Laws.—Many of the States have laws regulating the sale of concentrated commercial feeding stuffs. The laws usually require the feed to be true to name, and prohibit the sale of unwholesome feed. A guaranteed analysis is usually required, but some states require a guarantee of protein and fat only, others require crude fiber in addition to protein and fat, and still others require a guarantee of nitrogen-free extract in addition to the others. A guarantee of protein and fat is not sufficient to show the quality of the feed, and laws which require only such guarantee cannot be considered to provide sufficient protection.

It is not sufficient that the feed should come up to the guaranteed analysis, but it should be composed of the ingredients claimed, and no one should purchase a feed without knowing the feeding stuffs present. It is possible to make up the guaranteed analysis by means of substances of high composition but of low digestibility and low feeding value. Mixed feeds are often put on the market which contain ingredients that could not be readily sold separately, and are often sold at prices far in excess of their real feeding value.

The guaranteed analysis of a feeding stuff must, therefore, be regarded as a guarantee of the quality of the particular feed claimed to be sold. The fact that the feed comes up to the

guaranteed analysis is not necessarily proof that the feed is composed of the ingredients named, but the feed should be examined microscopically or otherwise when necessary. Two feeds of the same guaranteed analysis do not necessarily have the same feeding value, unless they are the same feed. A feed should be true to name, regardless of the guarantee. If foreign matter has been mixed with it, the feed is adulterated, regardless of the chemical analysis. Feeds are sometimes adulterated with other by-products of the same process of manufacture. Wheat bran may be adulterated with screenings; cottonseed meal may have such a quantity of hulls left in it that it is no longer entitled to be called cottonseed meal; an excess of hulls may be run into rice bran.

The term feeding stuff does not include indigestible materials, such as peat, earth, ground leather, sand, etc., or poisonous materials, such as poisonous plants, poppy seeds, castor-oil seed meal, etc. The value of a feed depends upon its nature and its chemical analysis. Chemical analysis alone is not sufficient, since materials vary considerably in digestibility and nutritive value, even with the same chemical composition. A microscopic examination is also necessary.

Injurious Feeds.—Rust and smut fungi sometimes cause disease or injury to animals eating the diseased feed. Moldy feed is liable to be dangerous to animals, as poisonous substances may be present. Yeasts found in by-products from beverages, etc., cause fermentation in the stomach. Boiling or steaming will obviate such danger. Frozen fodder feed in quantity is liable to cause digestive disturbances. When it thaws, it readily decomposes. Many kinds of weed seeds, such as field poppy, and corn cockles, have injurious effects. Sand, dirt, and ashes may cause no injury, but sometimes they give rise to serious digestive disturbances, constipation, or even death.

Percentage of Water.—The quantity of water in feeds, etc., may be seen on reference to the tables. Hay and straw contain 12-17 per cent., cereal grains 11 to 15 per cent., and oil cake and meal contains 6 to 13 per cent. Meals, cakes, and grain easily

undergo decomposition if they contain more than 14 per cent. water.

Preparation of Feeds.—Crushing or grinding the grain is often of advantage, especially for certain kinds of animals, or for those with defective teeth, when the grain is small or hard. The following shows the effect of feeding oats to horses, with chopped hay:

	Per cent. dry matter digested
Whole oats	64.6
Crushed oats	68.6
Coarse ground oats	72.7

Corn, rye, buckwheat, Kafir corn, milo maize, and leguminous seed, should best be ground for all animals. The following are some differences:

	Dry matter digested	
	Horses	Pigs
	per cent.	per cent.
Whole corn	82.5	74.4
Corn meal	89.5	88.4

In a number of experiments with pigs, the effect of grinding the corn was to reduce by six per cent. the quantity needed for the same gain in weight. Moistening the feed prevents its being blown away and prevents the fine particles of meal from getting in the eyes or lungs. Cooking, scalding, or steaming kills weed seeds, injurious molds or bacteria, and animal parasites, but as a rule, decreases the digestibility of the feed. Cooked or steamed food, however, is valuable for pigs. The following shows the effect of cooking:

	Digestibility of protein	
	Bran	Hay
	per cent.	per cent.
Not cooked	77.0	46.0
Steamed	70.0	30.0

Conditions of Growth.—The stage of growth, as we have already seen, affects the composition of the plant. Plants grown wide apart give coarser fodder than those sown thickly. Soil and manures also affect the nutritive values of plants, especially in meadows, where acidity or unfavorable soil conditions may promote the growth of plants not well suited for pasturage. Liming and drainage may encourage growth of clovers, vetches, and sweet grasses. Addition of nitrogenous manure may cause increased percentages of protein. Weather conditions also affect the quality of the plants. In wet years, the plant grows larger and is more woody. In dry season, the plant is short and compact.

Composition of Feeding-Stuffs.—The composition of feeding-stuffs shown in the various publications represents the average of variable analyses.[1] The average composition varies with different sections of the country, and for information in regard to the composition of local feeds, the student should consult the reports and Bulletins of his State Experiment Station. Reports of Feed Control officials also show the composition of concentrated feeding stuffs, while the guaranteed analyses are printed on the package, or a tag attached to it.

Concentrates.—The concentrates used in feeding are largely by-products from the manufacture of various articles. These feeding stuffs may be grouped according to their chemical composition or according to their origin. They are distinguished from roughages by being rich in protein or nitrogen-free extract, and low in crude fiber.

Classes of Concentrates.—Concentrated feeds may be arranged in six groups, according to their content of protein:

I. *Protein* 30 *to* 50 *per cent.*—Cottonseed meal, gluten meal, linseed meal, dried distiller's grains, peanut meal.

II. *Protein* 20 *to* 30 *per cent.*—Malt sprouts, gluten feed, cottonseed feed, dried brewers' grain, germ oil meal, whole pressed cottonseed.

[1] Bulletin 11, Office Exp. Sta.

III. *Protein* 14 *to* 20 *per cent.*—Wheat middlings, wheat bran, wheat shorts, oat middlings, flax feed, rye feed, cotton seed, sunflower seed.

IV. *Protein* 10 *to* 14 *per cent.*—Rice bran, rice polish, ground oats, ground wheat, barley meal, rye meal, hominy feed, oats mixed with barley.

V. *Protein* 8 *to* 10 *per cent.*—Corn bran, corn meal, corn chops, corn and oat feed, oat feed, dried beet pulp, beet molasses, kaffir corn, milo maize, corn and cob meal, sorghum seed.

VI. *Protein less than* 8 *per cent.*—Cane molasses.

Classes of Roughages.—Roughages may be divided into the following groups:

I. *Fodders.*—Corn fodder, corn husks, kaffir stover, sorghum. These contain from 3 to 12 per cent. protein and from 23 to 35 per cent. crude fiber.

II. *Cereal Straws.*—Oat, barley, rice, rye, and wheat straws, containing 3 to 6 per cent. protein and 35 to 40 per cent. crude fiber.

III. *Grass Hays.*—Bermuda, Johnson grass, timothy, millet, etc., containing 5 to 15 per cent. protein, and 22 to 35 per cent. crude fiber.

IV. *Legume Hays.*—Alfalfa, clover, cowpeas, peanuts, vetch, etc., containing 12 to 20 per cent. protein and 20 to 28 per cent. crude fiber.

V. *Waste Milling Products.*—Peanut hulls, corn cobs, cotton-seed hulls, oat chaff, oat hulls, rice hulls, wheat chaff, etc., sometimes mixed with concentrated feeds, but properly classed with roughage. They contain 2.5 to 5 per cent. protein and 30 to 48 per cent. crude fiber.

VI. *Fresh Grass or Fodder.*—Millet, oats, barley, sorghum, timothy, etc., contain about 80 per cent. water and 1 to 4 per cent. protein.

VII. *Fresh Legumes.*—Alfalfa, clover, cowpea, vetch, etc., containing 70 to 85 per cent. water and 2.5 to 5 per cent protein.

VIII. *Silage.*—Corn, sorghum, clover, usually corn containing 70 to 85 per cent. water and 1 to 4 per cent. protein.

IX. *Roots and Tubers.*—Carrots, potatoes, turnips, beets, etc., containing 70 to 90 per cent. water and 1 to 3 per cent. protein.

Description of Concentrates.—A few of these feeding-stuffs will be discussed briefly.

Cottonseed Meal is prepared by cooking and pressing the kernels of cotton seed. It contains 36 to 52 per cent. protein, according to its origin and freedom from hulls. The meal increases in protein from the eastern part of the country to the west, being richest in west Texas. The meal is often adulterated with hulls. The quantity of hulls may be roughly estimated by deducting 5 per cent. from the crude fiber and multiplying the remainder by 2¼. Thus a meal containing 10 per cent. crude fiber contains 10-5 x 2¼ = 11.3 per cent. hulls, approximately.

Brewers' grains are the dried residue from the treatment of cereals with malt, for the preparation of beer.

Pressed whole cottonseed is made by pressing the whole cotton seed between rollers. It thus contains all the hulls.

Wheat bran is the outer covering of the wheat grain. Sometimes the screenings, containing oats, weed seeds, wheat, etc., are mixed with the bran, with or without grinding. This is not allowable under most feed laws.

Alfalfa meal is ground alfalfa. It is properly a roughage and not a concentrate.

Rice bran is the outer coating of the rice grain, including some of the germ. It contains about ten per cent. each of protein and fat, but is liable to become rancid.

Rice polish is obtained in polishing rice. It contains some of the germ.

Corn bran is the outer covering of the corn grain.

Kafir corn and milo maize are similar to corn, but contain more protein. They have about 10 per cent. less feeding value than corn.

CHAPTER XIX.

DIGESTION.

Digestion converts food into forms which can be dissolved in water, or absorbed and utilized by the body. The digestive organs vary in size, shape, and capacity with different kinds of animals. Some animals, such as dogs, fowl, pigs, and men, have short digestive organs, adapted only to concentrated foods, such as meat, cereal grains, etc. The digestive organs of other animals, such as sheep, goats, cows, etc., are large and adapted to bulky food containing small amounts of nourishment. Horses and hogs have smaller digestive organs.

Outline of Digestive Process.—The first step in digestion is preparation of the food by chewing or grinding. This usually takes place in the mouth. The food is there moistened with saliva, a slightly alkaline liquid, which not only softens the food and lightens the labor of chewing, but contains an enzyme termed ptyalin which converts starch into sugar. Most of the work of digestion is performed by *enzymes,* substances which have the power of transforming other substances into simpler substances without themselves being changed. Ptyalin acts only in an alkaline medium, and as soon as the food becomes acid by fermentation or by means of the gastric juice, its action stops. Grinding or other preparation of the food before feeding will partly decrease the labor of chewing. Grinding is especially necessary for pigs, or for other animals when small hard seed are fed. When whole grain is fed to cattle, it is sometimes imperfectly masticated, and a considerable number of grains passes through undigested.

The sheep and the ox have four stomachs. The first and second stomachs are used to store the food until it is returned to the mouth for a second mastication. The food then passes to the third stomach, which has a sieve-like structure, where the food is kneaded and ground up. The digestion takes place in the fourth stomach.

These animals are called *ruminants,* and are able to utilize

coarser feed than animals which have only simple stomachs. Fermentation takes place in the first stomach of ruminants, since temperature and other conditions are very favorable to the action of bacteria. Lactic acid is produced from soluble carbohydrates, proteids are split up, amides are affected, and even crude fiber may undergo some slight change. Carbon dioxide, hydrogen, marsh gas, acetic acid, butyric acid, and lactic acid are some of the products of the fermentation. This process dissolves some of the nutrients, and breaks up the cell walls, thereby allowing the entrance of digestive juices. It also softens the materials and so favors the disintegration of hard vegetable structures when chewed again in the mouth. The acids which are formed gradually decrease the fermentation, until they finally stop entirely the action of the bacteria, since an acid medium is unfavorable to their activity.

Stomach Digestion.—When food enters the true stomach, the gastric juice is slowly poured upon it. The gastric juice contains hydrochloric acid, lactic acid, and three enzymes, which can act only in an acid medium. *Pepsin* splits up the proteids into albumoses and peptones. *Rennin* which is found largely in the stomach of young animals, coagulates the casein of milk and other proteids. *Lipase* splits fats and oils into glycerol and fatty acids. Proteids are digested chiefly in the stomach, though the fats are also split up and digested to some extent. The proteids are converted into peptones and albumoses, which are soluble and can pass through the membranes of the stomach. Even water-soluble proteids are split up during digestion.

Intestinal Digestion.—When the food enters the intestines, it is gradually mixed with bile, the pancreatic juice, and intestinal juices, and, being alkaline, they put an end to the action of the gastric juice.

Bile acts chiefly to form soaps with the fatty acids and to emulsify the fats and oils. The emulsion consists of minute drops of fat, suspended in the liquid, and both the emulsified fat and the soaps can be absorbed. Bile is also able to convert starch into sugar.

The pancreatic juice exerts a vigorous digestive action upon proteids, fat, and starch. It contains trypsin, which acts on proteids; amylopsin, which rapidly changes starch into sugar; and steapsin, which emulsifies and splits fat. The proteids are converted into crystallizable substances, such as leucin, tyrosin, aspartic acid, etc., as well as albumoses and peptones.

Intestinal juices also exert a digestive action, especially on protein and starch.

Bacteria increase in numbers as the food passes along the intestines; fermentation and putrefaction gradually supersede the action of the digestive juices. In herbivorous animals, digestion is aided by the enormous number of bacteria present in the lower portions of the intestines. These bacteria act upon the undigested food, split up fats, change starch, and other carbohydrates into lactic, butyric, and acetic acids, and exert considerable digestive action on crude fiber. Three gases, carbon dioxide, marsh gas, and hydrogen, are formed in the process. The crude fiber is digested only by such fermentation. A quantity of substances which would not be acted upon by the digestive juices are dissolved and made useful to the animal.

Absorption.—The dissolved nutrients are absorbed to some extent by the walls of the stomach, but most largely by the intestinal walls, and pass either directly into the blood, or first into the chyle and then into the blood.

The Proteids are taken up as albumoses, peptones, and, to some extent, as leucin, tyrosin, and other crystallizable nitrogenous bodies. But since these substances do not occur in the chyle or in the blood, they must have been synthesized into animal proteids in the membranes of the digestive organs. That is to say, the proteids of the food are first split up, then converted into necessary animal proteids. It is quite possible that some of the products of the digestion of the various proteids, are much better suited to the formation of animal proteids than others; and some products may be entirely unsuitable for the purpose of the

systhesis and must be oxidized.[1] It is also possible that the products of digestion of certain proteids may be injurious.

Fats are absorbed as fatty acids, as glycerol, as soaps, and in a finely divided form suspended in the digested solution, as an emulsion. There is a union of fatty acids and glycerol in the absorbing membrane, so that only fats enter the chyle or blood.

Carbohydrates are converted into simple sugars (grape sugar, fructose, etc.,) or by fermentation, into acids, such as lactic acid, butyric acid, etc. These appear to some extent in the chyle, but more largely in the blood.

Various methods are used in studying the processes of digestion. The digestive juices have been secured from animals, and their action tested upon various constituents of the food. The process of digestion has also been to some extent observed through openings made into the digestive organs by accident or intention. The contents of digestive organs have been removed and examined.

Rennet, prepared from the stomachs of calves; and pepsin, prepared from animals killed in the slaughter house, are commercial products, the former being used in coagulating milk in the manufacture of cheese, and the latter for medicinal purposes. None of the digestive ferments so far isolated have the power of causing crude fiber to go into solution. The intestinal bacteria, however, when inoculated into a medium containing crude fiber, cause it to be partly dissolved, producing marsh gas, carbon dioxide, organic acids, and soluble products which can be absorbed and utilized.

Excretion.—The undigested residues, mixed with gallic acid, mucus, with other animal products (metabolic products), and with digested but unabsorbed material, are finally ejected.

The excrement is by no means free of digestible materials. The quantity of digestible matter is small, however, unless the food is imperfectly masticated, or unless its premature evacuation is caused by digestive disturbances.

[1] See Wisconsin Research Bulletin No. 21.

The time required for the passage of food through the body varies with different kinds of animals. Residues of the food begin to appear in 12 hours with the dog, 36 hours with the pig, and three or four days in the excrement of the cow, sheep, goat, or horse. The residues are usually completely excreted in 7 to 8 days by cows, sheep, and similar animals, though bulky food may continue to appear for 14 days if followed by easily digested food, such as young grass, etc.

Metabolic Products.—The transformation which food undergoes within the animal is termed metabolism, and the products of the life action are termed metabolic products. The metabolic products in the excrement are residues of digestive juices and other animal products. A portion of the intestine, isolated but left within the body, has been found to collect a certain amount of waste material, which, under normal conditions, passes into the excrement. In ordinary digestion experiments, the metabolic products in the excrement may, for all practical purposes, be regarded as a portion of the undigested food, since they represent so much material lost from the body in the excrement. In other experiments, however, the metabolic products must be taken into account. The metabolic products contain protein, or fat and ash, but no carbohydrates or crude fiber. In some digestion experiments with food poor in fat, or with materials very poor in protein, more fat or protein has been found in the excrement than was present in the food eaten. The quantity of metabolic fat is, however, small, and of little importance.

The metabolic nitrogenous substances are of more importance. There are two ways of estimating the quantity of metabolic nitrogen. One method consists in feeding the animal on materials nearly free of nitrogen, and estimating the nitrogen in the excrement. For example, Pfeiffer fed hogs on potato starch, cane sugar, olive oil, and salts, a ration almost free of nitrogen, and found the excrement to contain 4.4 per cent protein. Kellner obtained similar results with sheep which were fed sawdust, sugar, and starch.

The other method does not give us the exact quantity of

metabolic protein, but gives the maximum quantity that may be present. Kuhn[1] has devised a method for estimating digestible protein, by means of pepsin and hydrochloric acid. By experiments on animals he has proved that the indigestible protein fed (estimated according to this method) is exactly equal to the indigestible protein excreted. That is to say, the animal cannot digest the protein found to be indigestible according to Kuhn's

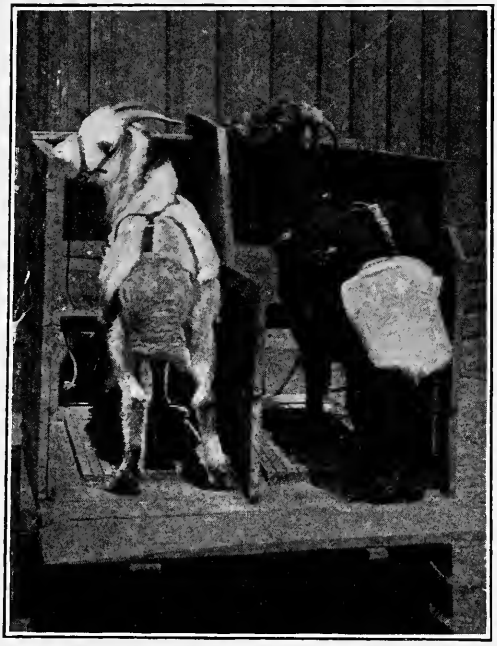


Fig. 83.—Goats ready for digestion experiment. North Carolina Station.

method. The metabolic products in an excrement, then, cannot be greater than the protein digested from it with pepsin-hydrochloric acid, though they may be less.

As a result of 20 experiments, Kuhn found from 0.36 to 0.58 gm. of pepsin-soluble nitrogen in excrement from oxen, with an average of 0.48 gm. for each 100 gm. of digested dry matter.

[1] Landw. Versuchs-stat., 1894, p. 204.

The averages of other workers are as follows: Pfeiffer 0.52 gm., Jordan 0.44 gm., Wolfe 0.47 gm. It appears that, on an average, not more than 0.45 gm. of metabolic nitrogen (equal to 2.8 gm. protein) is excreted per 100 grams of digested dry matter. Some metabolic mineral matter is also present in the excrement.

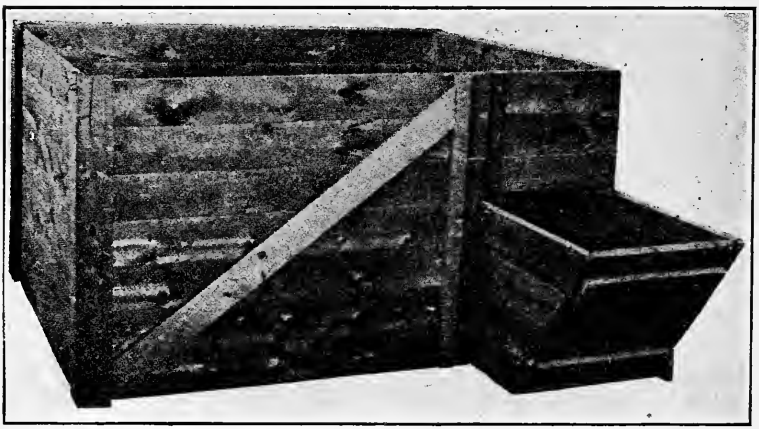


Fig. 84.—Stall used for digestion experiments with sheep. Wyoming Station.

Digestion Experiments.—The nutrients which disappear during the passage of food through the animal body are said to be *digested*. All that disappear do not pass through the membranes of the digestive organs, however, as some of them are converted into marsh gas and carbon dioxide by fermentation and escape as gases. The object of a digestion experiment is to determine, by trials on animals, the actual amounts of the different nutrients which are digested. In a digestion experiment, a known quantity of food is fed, the excrement from it collected, and both food and excrement are subjected to analysis. The quantity of each nutrient fed and digested is calculated, and the quantity of nutrient digested is divided by the quantity fed. The dividend, expressed as percentages, is the *coefficient of digestibility*.

With men, the faeces from different meals are not mixed in the body, and can easily be separated by appropriate means. Thus, at the meal before beginning the experiment, the man swallows a capsule of charcoal. Then for two or three days he eats the ration to be tested. At the end of the period he takes another capsule of charcoal. The dividing line between excrements from the meal without charcoal and the one with charcoal, is easily distinguished, and the excrement from the ration tested can be separated easily.

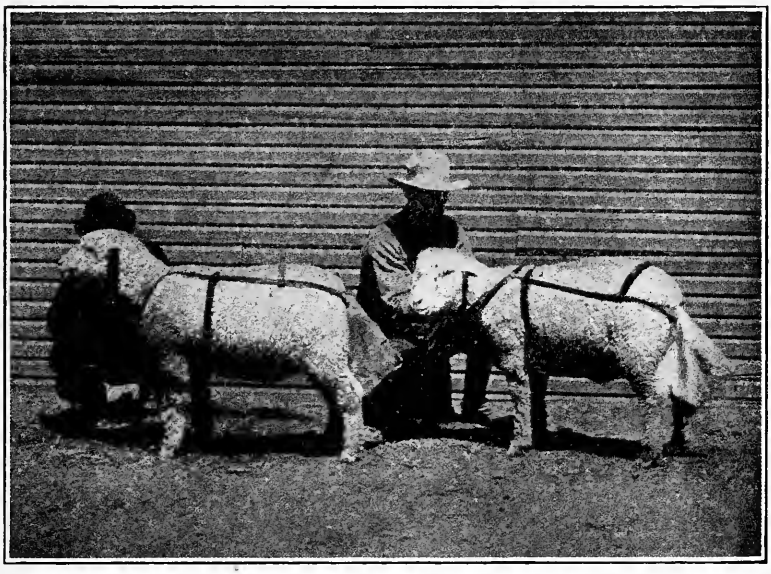


Fig. 85.—Sheep arranged for digestion experiment. Wyoming Station.

With domestic animals, the food from different meals is mixed so thoroughly in the stomach and intestines that not only is it impossible to distinguish one meal from another, but the residues from a given meal may appear in the excrement for three or four days. Such animals are fed a uniform quantity of food long enough to ensure the elimination of previous food residues, and the excrement is collected for a definite number of days. It

is assumed that the excrement corresponds to the food fed on corresponding days. This assumption is justified if the period of collection is long enough to compensate for the irregularities in elimination of the excrement. A period of only three or four days is likely to give incorrect results. The collection period should not be shorter than six days for pigs, eight days for sheep, and ten days for cattle.[1]

In digestion experiments with dry feeding-stuffs, a sufficient quantity of the feeding-stuffs should be secured before the experiment is begun. After ascertaining, by trial, how much the animal will eat, the feeding stuff should be mixed thoroughly, and the quantities to be fed each day should be weighed out carefully before beginning the experiment; at the same time, samples should be taken for analysis.

The animal is fed exactly the same ration for a period of from 16 to 18 days. The first 6 to 8 days feeding is for the purpose of eliminating residues from the previous ration, and is called the preliminary, or preparatory period. At the end of this period the digestion period begins, in which the excrement is collected for analysis. This lasts about 10 days. The excrement may be secured in rubber bags attached to the animal, or by special stall arrangements which prevent the solid excrement from being scattered or mixed with urine or bedding. With small animals, the excrement is collected every 24 hours, mixed thoroughly, and an aliquot part dried at a low temperature (60-70° C.). With horses and cattle, the aliquot should be taken every 12 hours, as the large masses remain warm and ferment rapidly. After drying, the samples are mixed and analyzed. If green feeds, silage, or similar materials are to be tested, equal quantities should be weighed for feeding each day, and a sample for analysis should also be taken every day and dried at once. The quantity of feed should be adjusted to the appetite of the animal before the preliminary feeding period begins. Residues, even when weighed and analyzed, introduce disturbances and diminish the value of the work.

[1] See Kellner, Exp. Sta. Record 9, p. 504.

If a concentrated feeding-stuff is to be tested, the digestibility of hay is first determined, then the concentrate added, and the digestibility of the mixture ascertained. The nutrients digested from the hay are subtracted from those digested from the mixture, and the difference is assumed to represent the material digested from the concentrate. It is assumed that ingredients of the mixture are digested to the same extent as the feeds would be separately, but this is not always the case, as we shall see. To guard against abnormal conditions of the digestive organs, and also to secure a more accurate average, at least two animals should be used.

The following is an example of an experiment[1] on one sheep. The preliminary feeding was eight days, and the digestion period, ten days. Three sheep were used, but the figures are given for for only one.

DIGESTION EXPERIMENT WITH ONE SHEEP.

	Protein	Fat	Crude fiber	Nitrogen-free extract	Water	Ash
Alfalfa hay fed, composition per cent.....	16.17	1.41	28.34	34.96	10.99	8.14
Excrement, sheep No. 2, composition per cent.	11.12	3.62	40.82	27.78	7.26	9.40
Fed 4,400 gms. alfalfa, containing gms.....	711.0	62.0	1,246.1	1.537.2	—	358.0
Excrement, 1,667 gms. containing gms.....	185.4	60.3	680.5	463.1	—	156.7
Digested	525.6	1.7	565.6	1,074.1	—	362.3
Percentage digested	73.9	2.7	45.4	69.9	—	56.0

Artificial Digestion.—By artificial digestion we mean laboratory tests to ascertain the digestibility of constituents of feeding-stuffs. Only with proteids has any measure of success been attained in this way. As before stated, the proteids not digested by Kuhn's method are not digested in the animal. Kuhn's method, then, offers us a means for ascertaining the *maximum digestibility* of the protein of feeding-stuff. The animal cannot digest any more proteids than is indicated by the method, though

[1] Bulletin 147, Texas Exp. Sta.

it may digest less. In Kuhn's method, 2 grams of feeding-stuff are treated with 1 gram of pepsin dissolved in 500 cc. of 0.2 per cent. hydrochloric acid, maintained at the blood heat 48 hours, and the hydrochloric acid increased from 0.2 to 1.00 per cent. by additions of acid at intervals of 12 hours. The residue is then filtered off, washed, nitrogen determined in it and calculated to protein.

Influence of Different Conditions on Digestion.—The digestion of food depends upon a number of conditions. The kind, variety, and age of the animal, composition of the rations, the preparation of the food, and other circumstances, have been studied by proper arrangement of the experiments.

Kind of Animal.—Differences in the digestive organs, digestive secretions, and habits of animals make considerable differences in their digestive power. The digestive organs of sheep and goats are twenty-seven times as long as their bodies; of the ox, twenty times; of pigs, fourteen times; and of the horse, eleven times. Ruminants have greater ability to digest coarse fodders than other animals. Sheep digest less than cattle, particularly of coarse fodders which are hard to digest, apparently because the contents of the last intestinal tract of cattle is more moist and the process of fermentation continues longer. The more digestible the material, the less the difference.

On account of shorter intestines and simpler organization of the stomach, the horse has a less digestive power than ruminants, especially for coarse fodders. The horse digests only about half as much from straw as does the ox. The difference is most marked with crude fiber and ether extract; there is little difference in protein, especially in concentrated feeds.

Pigs have less digestive power than horses or cattle for green feeds, and by-products containing much crude fiber. With grain and oil cakes the difference is less; but there are many by-products, such as brewers grains, which the pig digests poorly.

The following experiments were made to compare animals of different kinds, fed on the same fodder:

PERCENTAGES DIGESTED.

	Organic substance	Crude protein	Nitrogen-free extract	Crude fat	Crude fiber
Oat straw—Cattle	58	32	58	43	63
Sheep	48	19	49	50	49
Difference	10	13	9	—7	14
Meadow hay—Cattle	67	61	70	61	64
Sheep	65	57	69	57	61
Difference	2	4	1	4	3
Meadow hay, poor quality—					
Sheep	59	54	62	46	58
Horse	47	57	56	24	39
Difference	11	—3	6	22	19
Clover hay—Sheep	56	56	61	56	50
Horse	51	56	64	29	37
Difference	5	—	—3	27	13
Corn (grain)—Sheep	89	79	91	85	62
Horse	89	77	94	61	70
Difference	—	2	—3	24	8
Clover, young—Ruminant	74	74	83	65	60
Hogs	54	49	71	24	24
Difference	20	25	12	41	36
Corn (grain)—Ruminant	91	72	94	85	77
Hogs	90	79	94	74	44
Difference	1	—7	—	11	33

Other conditions regarding digestion by the animal which have been studied are as follows:[1]

1. Different breeds of the same animal have the same average digestive power.

2. Different *individuals* of the same variety may have different digestive power, due to faulty teeth, too rapid consumption of food, defective chewing, great nervousness, abnormal conditions of the digestive organs, chronic sickness, or defects of the digestive organs.

[1] Kellner, Ernahrung d. Landw. Nutztiere, p. 45.

3. The age of the animal has no influence, unless the animal is too young for the food given, or too old to masticate it properly on account of defective teeth.

4. Animals resting or at moderate work have the same digestive power. Vigorous work appears to cause a slight decrease.

5. Variations in light, temperature, and other external conditions, if great excitement is not caused thereby, have no effect.

Composition of Feed.—Different quantities of roughage fed alone are digested to the same extent. This is evident from the experiments of Henneberg and Stohmann with oxen, and E. Wolff with horses and sheep.

Daily ration weight of roughage	Dry substance	Percentages digested by sheep[1]			
		Protein	Fat	Nitrogen-free extract	Crude fiber
0.8	61	72	26	71	44
1.0	62	75	31	68	48
1.2	62	74	32	71	47

Different quantities of roughage and concentrates, mixed in the same proportions, appear to be digested slightly less with a heavy ration than with a moderate ration.

The addition of fat and oil does not affect the digestibility of the other nutrients, provided not over 1 pound per 1,000 pounds live weight is fed.[2] The oil must also be emulsified or finely divided, for liquid oil may occasion depression in digestibility, probably because it hinders the wetting of the food, and thereby the entrance of the digestive juices.

According to many experiments, the addition of digestible carbohydrates or non-protein will cause a depression of digestibility if the proportion of protein to carbohydrates is thereby made too wide. The following example is from Kuhn, in which starch was added to a ration of meadow hay fed to oxen.

[1] Landw. Versuchs-stat., 1878, p. 19.

[2] Kellner, Landw. Versuchs-stat., 1900, p. 114 and 199.

Assuming the starch to be completely digested, the results are as follows:[1]

PERCENTAGE DIGESTIBILITY.

	Organic substance	Protein	Fat	Nitrogen-free extract	Crude fiber
Meadow hay, alone	62.5	57.0	29.2	61.8	67.5
Meadow hay with 1,662 kg. starch	58.0	49.0	27.0	59.0	62.0
Meadow hay with 2,866 kg. starch	56.0	41.0	27.0	56.0	61.0

The depression in digestibility of protein may be in part due to increased excretion of metabolic products. As we have seen, 2.5-3.1 grams of protein are excreted from every 100 grams of digested dry substance, and the additional quantity of protein excreted corresponds very nearly to the increase which would be caused by the addition of starch. However, we do not yet know the cause of the decreased digestion. Other carbohydrates, as cane sugar, pectin, and purified cellulose, have the same effect as starch in decreasing digestibility.

An increase of protein can partly or completely eliminate the depression caused by addition of carbohydrates. For example, Haubner found that the starch appeared in the excrement of sheep fed on potatoes, but when rape cake was added to the ration, starch was no longer excreted. Many exact digestion experiments have proved that the addition of protein can increase the digestibility of a ration poor in protein.

Non-albuminoid nitrogenous compounds, such as asparagin, exert a similar effect. For example, Weiske found a ration nearly free of nitrogen digested 86 per cent., with addition of asparagin or fibrin it was digested 92 per cent. Kellner observed a similar action when asparagin or ammonium acetate was used.

Concentrated feeding-stuffs exert an influence on digestion according to their content of digestible protein or carbohydrates. Foods poor in protein, as beets and potatoes, exert a depressing

[1] Landw. Versuchs-stat., 1894, p. 470.

effect on digestibility, unless fed in connection with concentrates rich in protein. Concentrates of intermediate composition exert an appreciable effect upon digestion only when the ration contains more than 8 parts non-protein to 1 part protein. In general, it may be stated, that the digestion of a food is most complete when, for 7 to 8 parts digestible nitrogen-free nutriment (including fat $\times$ 2.25), not less than 1 part digestible crude protein is present. With pigs, which have a high digestive power for carbohydrates, the ratio may be as wide as 1 : 12.

Free acid, in moderate limits, has no influence upon digestibility. Experiments were made with sulphuric acid and lactic acid added to the ration of sheep and oxen, as much as 2.67 per cent. lactic acid being fed. Free acids are found in silage. Horses and young animals are often very sensitive to acid. The effect on the teeth must also be considered.

Carbonate of lime, even in high amounts, had no effect upon digestibility by sheep. Since the acid gastric juice could not have acted, being neutralized by the carbonate of lime, the work of digestion must have been performed by the alkaline pancreatic juice.

Character of Feed.—Dry fodder has the same digestibility as green fodder, when there is no loss in drying, but usually fermentation takes place, or leaves, etc., are broken off, leaving material of less digestible character. Young plants are, in general, more digestible than older ones, and also have a higher productive value. Corn, however, contains more digestible matter when fully ripe than if cut before the ears are grown. This is due to the production of a large quantity of highly digestible grain.

Stage of Growth.—The digestibility decreases with the stage of growth of the plant, more rapidly as the plant approaches maturity. An exception is Indian corn, which forms a large amount of easily digested grain as it approaches maturity.

B. E. Wolff obtained the following results with clover cut at different stages of growth:

PERCENTAGES DIGESTED.

	Nitrogen-free extract	Digested nitrogen-free extract and fiber
Green clover—		
Before bloom	43.5	51.9
Beginning to bloom	41.7	45.9
In bloom	47.9	47.5
End of bloom	43.8	42.6

Preparation of Food.—Cooking, steaming, roasting, etc., decrease the digestibility of the protein of the food. Grinding is better for hard seeds, or for those which are so small as to be liable to escape mastication, such as flax, barley, sorghum, millet, etc. Horses and hogs masticate food less thoroughly than ruminants, and hence derive more benefit from grinding.

The following are some American experiments[1] relating to these conditions:

COEFFICIENTS OF DIGESTIBILITY.

	Protein	Crude fiber	Nitrogen-free extract	Ether extract
Cottonseed, raw (cow)	67.8	75.5	49.6	87.1
Cottonseed, roasted (cow)	46.9	65.9	51.4	71.7
Decrease due to roasting	20.9	9.6	—1.8	5.4
Oat fodder, early cut (sheep)	72.3	54.6	63.5	70.2
Oat fodder, late cut (sheep)	67.8	43.5	61.1	67.5
Decrease due to late cutting	4.5	11.1	2.4	2.7
Timothy, full bloom (sheep)	60.4	62.1	71.8	51.5
Timothy, past bloom (sheep)	44.5	51.7	61.0	34.6
Decrease due to late cutting	15.9	10.4	10.8	16.9
Corn meal (pig)	86.1	29.4	94.2	81.7
Corn grain (pig)	68.7	38.3	88.8	45.6
Increase due to grinding	17.4	—8.9	5.4	36.1

[1] Bulletin No. 77, Office Exp. Sta.

Coefficients of Digestibility.—The following are coefficients of digestibility of a few feeding-stuffs.[1]

COEFFICIENTS OF DIGESTIBILITY OF SOME FEEDING STUFFS.

	Protein	Ether extract	Crude fiber	Nitrogen-free extract
Cottonseed meal	88.4	93.3	55.5	60.6
Cottonseed hulls	15.0	85.7	40.0	41.1
Wheat bran	77.8	68.0	26.6	69.4
Wheat shorts	79.8	86.3	33.1	81.3
Corn meal	67.9	92.1	—	94.6
Corn cobs	19.3	50.1	57.5	48.3
Rice bran	69.1	91.1	—	92.3
Rice polish	69.0	90.0	—	92.0
Alfalfa hay	75.3	40.5	46.4	68.4
Bermuda hay	57.5	43.3	54.9	51.5
Corn shucks	12.5	38.6	69.3	60.6
Johnson grass hay	43.9	44.6	66.2	56.8
Rice straw	26.6	36.4	58.0	47.3

Digestibility of Constituents of Nitrogen-Free Extract.[2]—Investigations as to the digestibility of the constituents of nitrogen-free extract, show that the sugars and the true starch are practically completely digested when the food is properly masticated. The pentosans are digested to about the same extent as the nitrogen-free extract, while the remaining and unknown constituents of the nitrogen-free extract have a much lower digestibility.[3] It

COEFFICIENTS OF DIGESTION OF CRUDE FIBER AND OF CONSTITUENTS OF THE NITROGEN-FREE EXTRACT.

Feed	Crude fiber	Nitrogen-free extract			
		Sugars	Starch	Pentosans	Residue
Kafir corn	—	86.2	97.4	—	—
Milo maize	—	100.0	99.6	—	—
Cottonseed meal and hulls	54.6	95.0	25.0	86.5	65.2
Timothy hay	52.3	100.0	—	58.0	50.0[4]
Crabgrass hay	67.3	100.0	—	61.0	32.7[4]

[1] Bulletins 147, 104, Texas Exp. Sta.; Bulletin 77, Office Exp. Sta.

[2] Headden, Bulletin 124, Colorado Station.

[3] Fraps, Bulletin 104, Texas Exp. Sta.

[4] Starch included.

is possible that the fermentation and other changes which food undergoes within the animal, modify the crude fiber so that a portion of it becomes soluble in acids or alkali, and thus appears as a portion of the nitrogen-free extract.

Digestibility of Ether Extract Constituents.—The ether extract of concentrates consists chiefly of fats and oils, but that of roughages contain on an average nearly 60 per cent. unsaponifiable matter, chiefly wax alcohols, as previously pointed out. It has been long observed that the ether extracts of hays and fodders have a low digestibility. Indeed, in a number of experiments, more ether extract was found in the excrement than was present in the hay.

A study of the digestibility of the constituents of the ether extract shows that while the unsaponifiable materials or wax alcohols have a low coefficient of digestibility, the saponifiable material, containing the fatty acids and chlorophyll, have a much higher digestibility. Thus the observed low digestibility of the ether extract of hays and fodders is due to the small content of fats and oils and the high content of waxes and alcohols less easily digested.

PERCENTAGE DIGESTIBILITY OF CONSTITUENTS OF ETHER EXTRACT.[1]

	Total extract	Unsaponifiable	Saponifiable
Alfalfa hay	4.9	—	59.1
Bermuda hay	46.9	31 2	69.0
Burr clover	—	—	8.6
Corn shucks	38.6	28.0	64.4
Johnson grass hay	52.2	47.0	60.1
Para grass hay	45.0	32.8	77.4
Millet	56.4	15.9	81.4

Composition and Heat Value of Digested Nutrients.—We may determine the composition of digested crude fiber by the following method: The crude fiber fed in the feed and the crude fiber excreted in the digestion experiment are subjected to analysis. The quantity of carbon, hydrogen, and oxygen fed in the crude

[1] Fraps and Rather, Bulletin 150, Texas Station.

fiber and the quantity excreted, is calculated from the known amounts of crude fiber fed and excreted. The quantity of crude fiber digested, and the quantity of carbon, hydrogen, and oxygen digested, are calculated from the data. From these figures we can calculate the composition of the digested crude fiber.

The crude fiber and the nitrogen-free extract in the excrement contain more carbon and hydrogen than that digested, and have a higher heat value. Digested crude fiber and digested nitrogen-free extract have been found to have the composition and heat value of a carbohydrate. For this reason, the digested crude fiber and nitrogen-free extract are often referred to as *carbohydrates*. The lignin is not digested.

The composition of digested ether extract, protein, etc., can be determined in the same way. The heat value of the digested nutrients is estimated by a procedure somewhat similar.

Ether extract of hays, grasses, and other coarse feeding-stuffs contain waxes, etc., as we have seen, which are not digested so well as fats. They accumulate in the excrement and change its composition. The composition and heat value of the digested ether extract is about the same as pure fat, while the ether extract in the excrement has a much higher heat value.

Proteids have a heat value of 5,479 to 5,990 cal. per gram. The digested proteids have practically the same value. The average is 5,711 calories.

HEAT VALUE OF CONSTITUENTS OF MEADOW HAY.

	Crude fiber	Nitrogen-free extract	Ether extract
Heat value of 1 gram feed	4,426	4,584	9,194
in Excrement	4,782	5,265	9,821
Digested	4,220	4,232	8,322

CHAPTER XX.

UTILIZATION OF FOOD.

Food is used by animals to maintain the body activities and restore waste of material. It is also used for the production of new material in growth and fattening, for milk production, and for energy to produce work. Whenever energy or heat are to be generated, oxygen unites with the substances, forming carbon dioxide and water from fats, organic acids, sugars, etc., and carbon dioxide, water, and urea or other nitrogenous waste products, from proteids. The carbon dioxide is eliminated by the lungs, and the nitrogenous waste passes off in the urine. The oxidation does not take place at one time, but a number of intermediate products are formed.

The following is the average composition of ten kinds of animals, according to analyses made by Lawes and Gilbert, at Rothamsted:

	Per cent.
Protein	13.5
Fat	28.2
Water	49.0
Ash	3.2
Contents of stomach and intestines	6.1
Total	100.0

The ash consists of approximately 86 per cent. calcium phosphate, and 12 per cent. calcium carbonate, with small quantities of fluorides, chlorides, iron, potash, and magnesia. These materials must all be supplied by the food.

Different nutrients of food have different values for the purposes above stated. The first bodily activity with respect to food is its mastication and digestion. This consumes food material, which although derived from food previously eaten, must be replaced by the food being eaten. Different kinds of food require different amounts of energy in mastication and digestion.[1]

The food material remaining after deducting the losses due to mastication, digestion, and undigested residues, may be used for

[1] Hagemann, Exp. Sta. Record 10, p. 906.

the purposes of the body. The necessary vital functions must first be subserved, such as the body heat, beating of the heart, movements of the lungs, etc., and all other functions necessary for the maintenance of the life of the animal.

Any food values remaining after maintaining the animal, may be used for productive purposes, such as work, building of fat or flesh, production of milk, etc.

The utilization of the various foods and nutrients by the body is studied by means of exact experiments on animals. The experiment must, of course, be adapted to the end in view. A study of the income and outgo of nitrogen is called the nitrogen balance. A loss of nitrogen means a loss of flesh; a gain of nitrogen, a gain of flesh. The income and outgo of carbon, taken in connection with the nitrogen balance, gives the loss or gain of fat. This is called the carbon balance. The determination of the income and outgo of energy is called the energy balance.

The Nitrogen Balance.—In order to determine the exact amount of nitrogen the animal is gaining or losing, we proceed as in a digestion experiment, but collect and analyze the urine in addition to the solid excrement.

The total quantity of nitrogen in the food fed is the income of nitrogen. The nitrogen in the solid excrement is undigested material; that in the urine, is the digested nitrogen which has undergone complete metabolism in the body. The nitrogen in the perspiration is so small that it is usually not considered.

Income in food less outgo in solid and liquid excrement is the loss or gain of nitrogen. If income is greater than the outgo there is a gain; if less, a loss of nitrogen. Since over ninety per cent. of the nitrogen in the animal body is in the form of flesh, a loss or gain of nitrogen represents a loss or gain of flesh.

Water and fat-free flesh has been found to contain, on an average, 16.67 per cent. of nitrogen and 52.54 per cent. of carbon. That is, 1 gram of nitrogen is contained in 6 grams of dry flesh, which also contains 3.15 grams carbon. Flesh contains on an average 77 per cent. water. Hence a gain of 1 gram of nitrogen

means a gain of 3.17 grams of carbon in dry flesh, and a gain of 26 grams of moist flesh or muscular tissue.

The Carbon Balance.—Carbon enters the animal in food and water, and leaves it in urine, solid excrement, perspiration, and as the gaseous bodies-carbon dioxide and marsh gas. The marsh gas and part of the carbon dioxide comes from the fermentation in the intestines, but most of the carbon dioxide comes from oxidation of carbonaceous bodies in the animal. For example, the air inhaled and expired by a horse was found to have approximately the following percentage composition:

	Inhaled	Exhaled
Oxygen	20.96	16.00
Carbon dioxide	0.03	4.40

The following table gives an example of the determination of the carbon and the nitrogen balance:

CARBON AND NITROGEN BALANCE.[1]

	Nitrogen	Carbon
	grams	grams
Income per day:		
4.36 kg. meadow hay	69.96	2,010.8
3.52 kg. dried beet residue	50.9	1,572.0
0.87 kg. rye bran	27.50	408.8
0.27 kg. gluten meal	37.05	138.4
3.42 kg. starch	2.01	1,443.0
36.09 kg. drinking water	—	2.7
Total income	177.47	5,575.5
Outgo per day:		
3.44 kg. solid excrement	106.55	1,609.6
kg. urine, containing	73.69	170.9
Expired carbon dioxide	—	3,112.5
Total outgo	180.24	4,892.0
Gain by body	7.23	672.5

The gain of 7.23 grams of nitrogen means a gain of 7.23 times 6 equals 43.4 grams of dry flesh, containing 22.8 grams of carbon.

[1] Kellner, Landw. Versuchs-stat., 1900, p. 4.

This quantity of carbon, subtracted from 672.5 grams, leaves 649.7 grams carbon, which is contained in 849.3 grams of fat, since beef fat contains 76.5 per cent. carbon. Hence this animal gained 43.4 grams of flesh and 849.3 grams of fat per day:

Apparatus to Determine the Carbon Balance.—The respiration apparatus[1] consists essentially of an air-tight chamber to hold the animal, provided with a window and door and suitable openings for the introduction of food and water. A current of air is sucked through the apparatus by a ventilating fan connected with a gas meter for measuring the volume of the air drawn through. A portion of the air entering the chamber is sucked out by a mercury pump and measured by a small gas meter. It then passes through a series of tubes containing a solution of barium hydroxide, of known strength, to absorb the carbon dioxide. Barium carbonate is precipitated, and the excess of barium hydroxide can be determined by titration with an acid of known strength. The carbon dioxide may also be absorbed by soda lime and weighed. This gives the amount of carbon dioxide in the air subjected to analysis, and the total quantity contained in the known quantity of air which passes through the respiration chamber can be easily calculated. Another measured portion of the air passes through a tube containing copper oxide, heated red hot by means of a combustion furnace, and then through a second series of barium hydroxide tubes. The marsh gas or other organic carbon compounds are oxidized in the tube to carbon dioxide, which is absorbed by the barium hydroxide as before. We thus know the total quantity of carbon as carbon dioxide and as organic carbon, which goes into the respiration chamber with the air taken in.

Measured portions of the air which goes out of the chamber are withdrawn, and passed through an apparatus exactly similar to that described above. The exact quantity of carbon in carbon dioxide and in organic forms given off by the animal, is the difference between that in the air which leaves and that which enters the respiration chamber.

[1] Exp. Station Record 10, p. 813.

Energy Balance.—The energy balance may be determined in two ways:

First, the energy in the food fed, and in the solid and the liquid excrement may be determined by direct measurements, and that lost as marsh gas calculated. The heat value of the fat or flesh gained or lost may be calculated from the loss or gain of fat and flesh found by the nitrogen and the carbon balance. From these figures we estimate indirectly the energy used by the animal body.

Second, the determination of energy in the food and in solid, liquid, and gaseous excrements is made as stated above, but the energy given off by the animal is measured directly. This form of experiment requires the use of a *respiration calorimeter*.[1] The results of the two methods should, of course, agree, but the second method is adapted to studying problems which cannot be solved by the first. For example, the energy given off during the time digestion is going on may be compared with that given off when no digestion is going on. In experiments with human beings, the extra energy given off during reading, work, etc., may be determined.[2]

Respiration Calorimeter.—A respiration calorimeter consists of a respiration chamber arranged so that the heat given off by the animal can be measured. The chamber is insulated so that as little heat as possible may be lost or gained by it. The incoming air is cooled to a uniform temperature, and the outgoing air is cooled to the same extent. The heat given off by the animal is taken up by water circulating through tubes inside the chamber. The temperature of the water is taken before it enters the chamber, and when it leaves. The volume of water and the difference in temperature of the incoming and outgoing water being known, the heat eliminated is easily calculated to calories.. Allowance is also made for the heat changes involved in the condensation of water on the sides of the chamber, and for evaporation during the experiment.

[1] Armsby, Bulletin 104, Pennsylvania Station. Exp. Sta. Record 15, p. 1033.

[2] For description of human calorimeter see Bulletin 63, Off. Exp. Station.

A respiration calorimeter is a complicated and expensive apparatus, but it secures information regarding the use of nutrients and the nutrition of the animal which is of the highest value, and which can be secured in no other way.

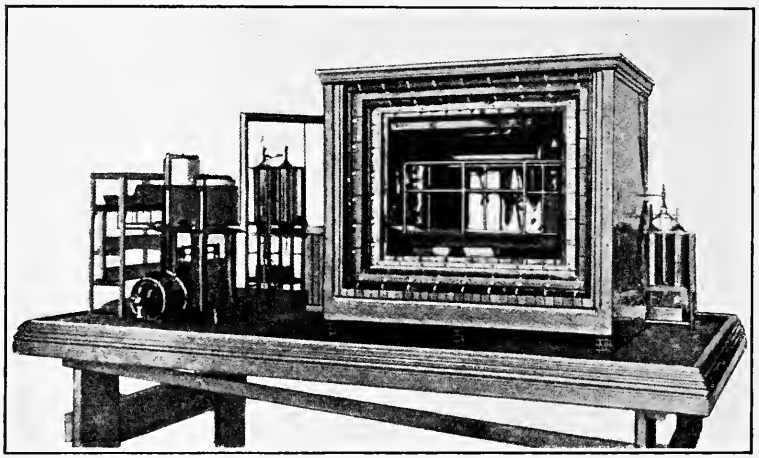


Fig. 86.—Model of respiration calorimeter at the Pennsylvania Station. U. S. D. A.

Disposition of Food Materials.—The *carbon* which enters an animal in food, is disposed of as follows:

(1) A portion appears as undigested material in the solid excrement.

(2) A portion escapes as marsh gas and carbon dioxide, produced by fermentation.

(3) A portion is eliminated as partly oxidized compounds in the urine.

(4) A portion is eliminated as carbon dioxide in the gases expired from the lungs, being fully oxidized in the body.

(5) A portion is used in the production of hair, flesh, fat, milk, etc.

The *nitrogen* appears as follows:

(1) In the undigested residues.

(2) In the urine.

(3) In perspiration (very small quantity).

(4) Used in the production of hair, flesh, milk, etc.

The *energy* is used as follows:

(1) A part appears in the undigested solid excrement.

(2) A part is used in fermentation and escapes as heat.

(3) A part is lost in incompletely oxidized organic matter in the urine.

(4) A part escapes in marsh gas produced by fermentation in the intestines.

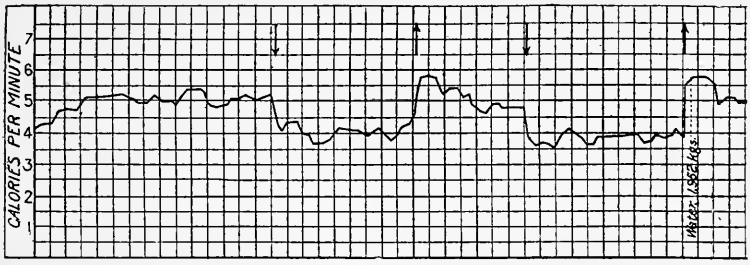


Fig. 87.—Curve showing heat production of steers in respiration calorimeter, the arrows being pointed up if the animal is standing. Pennsylvania Station.

(5) A portion is used to masticate and digest the food, and is eliminated as heat.

(6) A portion used for bodily activities, such as beating of the heart, breathing, movements, warming the body, etc., and is eliminated as heat.

(7) Any portion remaining after the above requirements are satisfied, may be used for external work, stored up in fat or flesh, or used in the production of milk, etc.

Production of Marsh Gas.—The effect of different nutrients or foods upon the production of marsh gas has been studied by the following method. First, the quantity of marsh gas evolved with

a given ration is exactly determined in the respiration chamber. Then the marsh gas evolved with the same ration plus fat, protein, starch, crude fiber, or any other nutrient or feed, is determined. The increase or decrease in the quantity of marsh gas evolved, shows the effect of the addition.

In this way it was found that fat and proteids do not affect the quantity of marsh gas. The methane appears to come entirely from the constituents of the nitrogen-free extract and crude fiber. The ratio of protein to non-protein, and other factors, also appears to affect its production. All additions which decrease the digestibility of the nitrogen-free extract decrease the production of methane, but in greater proportion; and additions which increase the digestibility of the nitrogen-free extract increase the production of methane. The various factors which affect the production of methane require further study.

A considerable portion of the value of the digested nitrogen-free extract and crude fiber is lost as marsh gas, as is seen from the following table:

	Sugar	Starch	Crude fiber (paper starch)	Nitrogen-free extract and crude fiber (average of 100 experiments)
Grams methane for 100 grams digested.....	2.84	3.17	4.46	4.29
Heat value of methane.	37.9 Cal.	42.3 Cal.	58.6 Cal.	57.2 Cal.
Heat value of substance	395.5 Cal.	418.3 Cal.	418.5 Cal.	418.4 Cal.
Percentage loss.....	9.6	10.1	14.0	13.7

A considerable percentage of the material which does not appear in the solid excrement during a digestion experiment is not really digested, i. e., converted into soluble products and absorbed by the body, but is fermented and a portion of its value is lost as marsh gas.

Organic Matter of the Urine.—The digested nitrogenous bodies which have been oxidized by the animal body are excreted in the urine, in the form of urea $CO(NH_2)_2$, uric acid $C_5H_4N_4O_3$, creatin $C_4H_9N_3O_2$, or hippuric acid, $C_6H_5CO.NHCH_2COOH$,

and possibly other compounds. All these substances are incompletely oxidized, and represent a loss of energy from the food. Non-nitrogenous organic substances are also present in the urine.

For example, the following is an analysis of the urine of a sheep:

Water	86.48
Urea	2.21
Hippuric acid	3.24
Ammonia	0.02
Carbonic acid	0.42
Other organic substances	2.07
Ash	5.56
	100.00

The effect of various substances upon the urine may be studied by determining the amount and composition of the urine with a given ration, adding the substance to be studied to the ration, and determining the change in the urine caused by the addition. This effect is usually expressed in terms of energy (calories). Kellner,[1] assuming that only the proteids fed affected the loss of energy in the urine, obtained the following results with certain concentrates:

Average energy in 1 gram digested proteids, Calories	5.71
Average loss of energy in urine from 1 gram, Calories	1.29
Average percentage loss of energy in urine	22.6
Maximum percentage loss (with linseed meal)	26.6
Minimum percentage loss (with gluten meal)	18.9

The assumption of Kellner, however, is not correct, since the other constituents of the food have some effect upon the loss of energy in the urine. Only traces of sugar or pentosans are found in normal urine, but an addition of roughage to a ration increases the loss of energy in the urine to a considerably greater extent than the addition of an equal quantity of protein in the concentrated feeding-stuffs mentioned above. Sometimes the increased loss is greater than the quantity of energy in the proteids fed in the roughage. Non-nitrogenous substances, therefore,

[1] Die Ernahrung d. Landw. Nützture, p. 83.

suffer a loss of energy in the urine, but at present little is known as to the nature of this loss and what factors modify it.

Available Energy.—A portion of the energy in the food fed to the animal remains in the undigested matter of the solid excrement, a portion appears in the urine, and a portion is lost in the form of marsh gas. None of the energy so lost is of any value to the animal, and may be termed unavailable energy. The *available energy* is the total energy in the nutrients less the losses in the solid, liquid, and gaseous excrements. A portion of the available energy is expended in the processes of mastication, moving the food, preparation of digestive juices, digestion, and other operations necessary to bring the digested nutrients into the body, and convert them into forms suitable for its use. This energy does not, of course, come from the food actually in process of digestion, but the digested food must replace the energy so used. The energy used in digestion, etc., appears as heat, and may aid to keep the animal warm, but any excess over the amount so required, serving no useful purpose, is evolved as heat. We will term the energy consumed in digestion of the food *thermal energy*.

The available energy remaining after the thermal energy has been subtracted, may be used for processes requisite to the life of the animal, such as to keep the animal warm, to furnish energy for beating of the heart, breathing, and necessary movements of the body. Any excess over that needed by the animal body may be used for productive purposes—for fat, flesh, milk, etc. We will term this portion of the energy of the food its *kinetic energy*.

Estimation of the Energy Expended in Digestion.—Two methods may be used to estimate the energy expended in digestion of food. The first method can be applied only to animals, such as the dog, having small digestive organs, which can be completely emptied by starving for a few days. The heat evolved from a starving dog at a temperature of 33° is measured by placing the animal in a calorimeter. Sufficient food is then given to supply an amount of available energy equal to that lost daily while starving, and the heat liberated is again measured. Any increase

in the amount of heat evolved is due to processes essential to the digestion of the food, since at 33° no heat is required to maintain the body temperature of the animal. The heat evolved during starvation being put at 100, the heat evolved during the same length of time when food containing an equal amount of *available* energy (100) was fed was found by experiments of Rubner[1] to be as follows:

	Heat evolved in starvation 100
Heat when 100 calories flesh was fed	130.9
Heat when 100 calories fat was fed	112.7
Heat when 100 calories gluten was fed	128.0
Heat when 100 calories cane sugar was fed	105.8

That is to say, the consumption of the food caused an increased production of heat, which was probably due to digestion of the food. Since 100 calories of available energy was fed, the increased quantity of heat evolved represents heat evolved by the digestion; that is, the percentage of thermal energy contained in the available energy. This ranged from 5.8 per cent. with the sugar to 30.9 per cent. with the flesh.

The second method is applicable to herbivorous animals, but gives only indications. The animal is fed on a ration, and the heat evolved from the body is measured. The feed to be studied is added to the ration and the heat is again determined. The increase in heat is due to the digestion of the added feed.

The following figures of Armsby[2] afford an illustration:

	Heat in feed digested	Heat produced by animal
Period I	6,618	9,067
Period II	9,482	10,206
	+2,864	+1,139

An increase of 2,264 calories in the digested food caused an increase of 1,139 calories in the heat given off by the animal. That is, about 34 per cent. of the energy of the food was consumed in digestive processes.

[1] Quoted by Kellner, Die Ernahrung d. Nützliere, p. 105.
[2] Proc. Soc. Prom. Agr. Sci., 1902, p. 100.

The Productive Value of a Nutrient.—As we have previously stated, the quantity of a ration in excess of the maintenance requirements of an animal, may be used for productive purposes. If the animal is a fattening animal, this excess may be used for putting on fat.

Kellner[1] has estimated the fat produced by various nutrients and feeds by the following method. With the aid of the respiration apparatus, he determined the income of carbon and nitrogen in the food fed and in the water, and the outgo in the urine, the solid and the gaseous excrements, and so ascertained the quantity of the fat and flesh produced by a basal ration (Period I). This ration was sufficient to maintain the animal and produce a little fat. In Period II, the nutrient or food to be tested, was added to this basal ration and the amount of flesh and fat produced was again determined. The small quantity of flesh gained or lost was in each case calculated to the quantity of fat which would contain an equal amount of energy. The amount of fat gained in Period II less the amount of fat gained in Period I, gives the gain of fat due to the additional food or nutrient fed. The quantity of fat produced by 100 grams of the food or nutrient digested was then calculated from this data. The quantity of fat produced should be in proportion to the kinetic energy of the feed.

Experiments were first made with pure nutrients, with the following results:

	Fat produced by 100 grams digested
Cocoanut oil	59.8
Ether extract of coarse feeding stuffs	47.4
Ether extract of grasses	52.6
Starch	24.8
Cane sugar	18.8
Lactic acid	0.0
Crude fiber (paper pulp)	25.3
Proteids (albumen)	24.8
Pentosans	not determined

[1] Landw. Versuchs-stat., 1900, p. 450. See also Armsby, Bulletin 71, Pennsylvania Station.

Productive Value of Feeds.—The substances thus mentioned represent the various groups of constituents of a feeding-stuff.[1] Kellner determined the composition and digestibility of a number of feeding-stuffs, and calculated the quantity of fat which each could produce, based upon the values given in the preceding table for the digestible nutrients. The following is an example of the method of calculation used:

COTTONSEED MEAL.

	Digested	Fat produced by 1 gram	Total fat
	grams		grams
Protein in 100 grams	39.6	0.235	9.30
Fat in 100 grams	13.0	0.598	7.77
Carbohydrates (including crude fiber)	12.1	0.248	3.00
Calculated total for 100 grams	—	—	=20.07
Found by experiment	—	—	19.62

Thus 100 grams of cottonseed meal should produce 20.07 grams fat under the conditions given. We will term this the *productive value.*

If the value of a feeding-stuff for producing fat is in proportion to the quantity of digested nutrients present, i. e., if the digested nitrogen-free extract etc., of one feed has the same value as that of any other (as has heretofore been assumed), then the above method of calculation should be correct.

The results of a number of experiments and calculations are given in table on following page:[2]

The calculated quantity of fat is, in many cases, much greater than that actually found by experiment. That is to say, the productive value of different kinds of feeds is not necessarily in proportion to their content of digestible nutrients.

[1] See also Hagemann, Exp. Sta. Record 10, p. 907.

[1] After Kellner, Die Ernährung d. Landw. Nütztiere, p. 163.

FAT PRODUCED BY 100 GRAMS OF THE FEEDS NAMED.

	Calculated from digested nutrients	Found by experiment	Percentage of calculated
Peanut meal	18.9	18.9	100
Palm nut meal	17.9	18.3	102
Linseed cake meal	19.7	19.2	98
Rice meal	16.8	18.3	108
Rye meal	18.1	16.9	93
Bean meal	17.3	16.3	94
Rye bran	15.8	12.5	79
Wheat bran	15.4	11.9	77
Brewers grain (dry)	15.4	13.0	84
Potatoes	18.5	18.1	98
Sugar beets	15.0	13.1	87
Beet residue (wet)	18.1	17.4	94
Beet residue (dried)	18.1	14.2	78
Wheat straw, I	10.4	2.1	20
Wheat straw, II	8.4	2.4	29
Oat straw	10.9	6.6	59
Barley straw	11.7	7.8	64
Meadow hay, I	12.9	8.1	54
Meadow hay, II	15.6	10.9	55
Clover hay	12.4	8.5	63
Grass hay	13.3	8.5	64

Relation to Character of Feed.—The production of fat from the oil meals, potatoes, and rice meal was equal to that calculated. With rye meal and bean meal it was about 94 per cent. The beans and dried beet residues were deficient to the extent of 21 to 23 per cent. The values of none of the concentrated feed-stuffs fell below 77 per cent. of the calculated.

The fat production found to take place with the hays and straws was 20 to 64 per cent. of the calculated quantity. The deficiency was found to be related to the total quantity of crude fiber in the feed. For example, 100 grams of wheat straw No. 1 produced 8.3 grams less of fat than the calculated quantity, and contained 46.6 grams of crude fiber; that is, there was a deficit of 0.18 gram of fat for each gram of crude fiber present. For eight straws and hays, the maximum deficiency of fat per 1 gram of crude fiber present was 0.18 gram, the minimum being 0.11, and the average 0.14 grams.

This deficiency is in part due to the work of chewing the feed. A number of experiments were repeated after grinding the feed,

with the result that the average deficit was found to be only 0.073 gram of fat per 1 gram of crude fiber fed. The deficiency was no doubt due in part to the character of the nitrogen-free extract of hays and straws, which, as is well known, is not composed of sugars and starch, but largely of substances hard to dissolve and in part of unknown nature. They are not the same as the starch used by Kellner to represent the pure nutrient.

Calculating Productive Value.—Knowing the composition and coefficient of digestibility, the productive value in terms of fat of a given feeding-stuff may be calculated so as to be in accord with the experimental work cited. The results are expressed in pounds fat which may be produced by 100 pounds of feed.

Concentrated Feeding-Stuffs.—Multiply digestible proteids in 100 pounds fed by 0.235. Multiply digestible fat by 0.598. Multiply digestible nitrogen-free extract and crude fiber, taken together, by 0.25. Add the products, and multiply by the percentage of fat produced by the feeding-stuff in question as per preceding table. If the feeding-stuff is not named in the table, it will be necessary to use the factor for the feed most closely resembling it. The result is approximately the productive value in terms of fat. Chaff, rice hulls, and other by-products high in crude fiber are not considered as being concentrated feeding-stuffs.

Roughage.—Proceed as directed above, using the factor 0.526 for digestible ether extract in grasses, and 0.474 for all other roughages, and sum up the fat values of the nutrients. Then, if the roughage is not ground, multiply the total quantity of crude fiber present in 100 pounds by 0.14 and subtract this quantity from the sum. If the roughage is ground, multiply the crude fiber by 0.07 and proceed as before. With green feeds containing 8 per cent. or less crude fiber, deduct 0.085 gram fat for each gram of crude fiber; with those containing 8 to 10 per cent., deduct 0.095; with those containing 10 to 12 per cent., deduct 0.108; with those containing 12 to 14 per cent., deduct 0.12; 14 to 16 per cent., deduct 0.135; over 16 per cent., deduct 0.14.

The following is an example of the method of calculating the fat value of a roughage:

Johnson Grass Hay 100 Pounds.		
Digestible protein	3.3×0.235	$= 0.78$
Digestible fat	0.7×0.474	$= 0.33$
Digestible crude fiber	22.6	
Digestible nitrogen-free extract	28.1	
	50.7×0.25	$= 12.42$
Total		13.53
Total crude fiber	38.0×0.14	$= 5.32$
Productive value		8.21 pounds fat

This means that 100 pounds of the Johnson grass hay added to a ration already sufficient to maintain the animal, should produce 8.21 pounds fat. The fat value is the productive value for fattening, when the feed is used for fat and for no other purpose.

Kellner expresses the productive value of feeds and rations in terms of starch; that is, the quantity of starch which is capable of producing the same quantity of fat as 100 pounds of the feed is capable of producing. Armsby[1] expresses the productive value in terms of heat units (therms). There are two objections to this manner of statement. The first is, that the heat units are used for the total heat value of the feed, for the available heat value, and for the productive value, introducing some confusion in distinguishing between them. The second objection is, that the energy equivalent to the quantity of fat produced is not the productive energy of the feed, since no doubt some of the energy must be consumed in the process of transforming the nutrients into fat. The productive energy may be proportional to the fat produced, but is not identical with it.

We therefore prefer to express the productive value of feed in terms of the actual experimental basis, namely, of the fat which they were found to produce.

The productive value of a feed may be defined as the quantity of fat which the feed will produce, when it is fed in addition to a ration already sufficient to supply the needs of the animal for maintenance.

[1] Farmers Bulletin No. 346.

Significance of the Productive Value.—We have seen that a portion of the value of a food is lost in undigested material, a part as marsh gas, or oxidized in fermentation, a part in the incompletely oxidized material of the urine, and a portion is used for digestion and other processes fitting it for the use of animal. What remains of the food after these losses are deducted, may be used for maintenance, work, fat, flesh, milk, etc. It represents the *net value* of the food to the animal. It also corresponds to what we elsewhere termed the *kinetic energy* of the food.

The *productive value* of a food is the best measure so far devised for the net value of a food. Rations have heretofore been calculated on the assumption that all digestible nutrients of the same group have the same value to the animal, regardless of the origin of the material. We now know, however, that the net value of a food may vary widely from its value based entirely on digestible nutrients, so that the value of a food for the purpose of producing energy is best measured by its productive value.

It is quite possible that the kinetic energy of different feeds undergo somewhat different losses when transformed into fat, so that the quantity of fat produced may not be the most exact possible measure of the net values of feeds. The energy used in digestion and given off as heat may also prove useful under certain circumstances, such as with an animal on a maintenance ration in cold weather.

While the fat values of feeding-stuffs probably represent their comparative values for fattening purposes, and perhaps for milk, it does not follow that they represent the values of the feeds for productive work and for maintenance of the animal. The conversion of proteids, etc., into fat undoubtedly consumes energy, and a greater quantity of energy may be required to convert the proteids of one feeding-stuff into fat, than those of another; whereas if the kinetic energy is used directly for work or maintenance, these proteids might be equal in value for these purposes. We have seen that a feeding-stuff possesses both kinetic and thermal energy, and that the thermal energy may be used to keep the animal warm. While the thermal energy fed to an

animal on a heavy ration may be so excessive that differences in the thermal energy of feeds may have no significance, an animal on a small or maintenance ration, may be able to utilize the thermal energy.

The use of the productive value of a feed is no doubt a decided advance in the science of animal nutrition, as it emphasizes the differences in the productive values of the digested nutrients of different classes of feeds. It is clear that the digested nitrogen-free extract, for example, of hays and fodders, does not have the same value to the animal as that of grains and other concentrates.

The value of a feed for nutrition is thus indicated by:

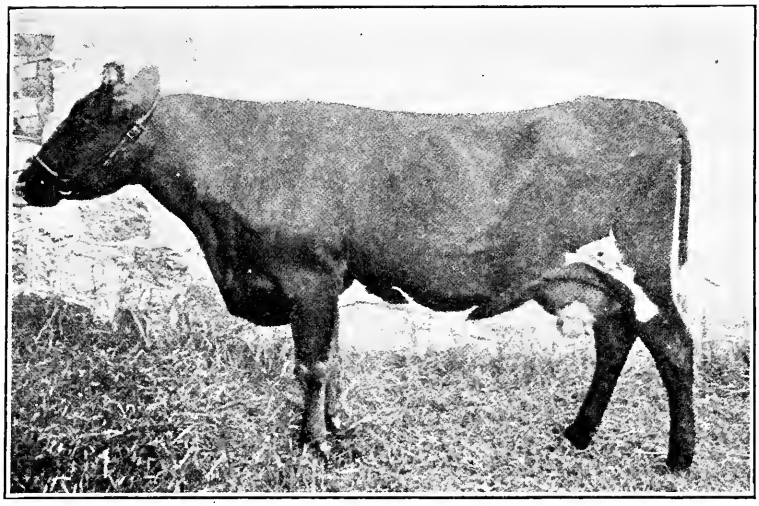
(1) Its content of digestible protein, or power to produce flesh.

(2) Its productive value in terms of fat, or its power to produce fat.

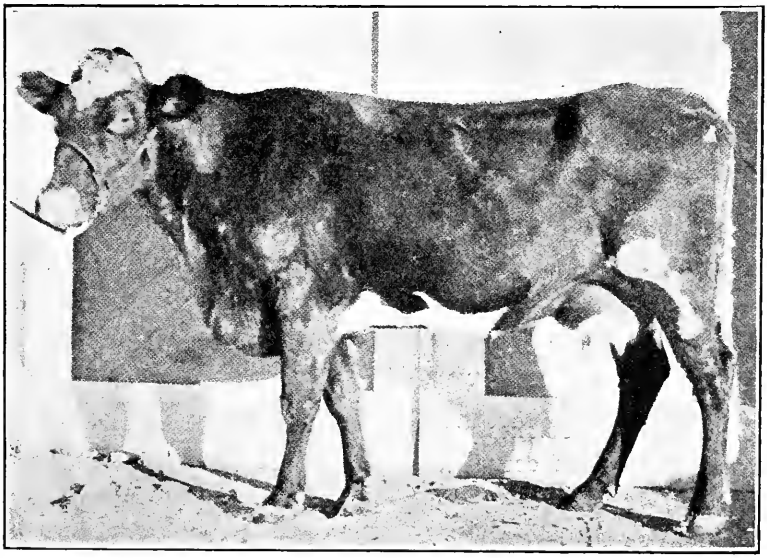
Mineral Materials.—Animals require inorganic as well as organic materials.[1] The term "inorganic" is not strictly accurate when used in connection with phosphates, as the phosphorus is partly in organic combination. However, any addition of phosphates to the ration is made as inorganic substances. Ash is left by all organs of the body when burned, and mineral matter appears essential to their proper growth and development. Mineral substances are required in processes of digestion and metabolism. Animals fed on food from which the ash has beeen extracted become irritable, nervous, show weakness of the extremities, and die sooner than if not fed at all.

The most important inorganic substances are salt, phosphoric acid, and lime. Salt is found in the digestive juices. In moderate amounts, it appears to favor the retention of proteids by the body. Cattle of average weight should receive 20 to 25 grams; sheep and pigs, 4 to 8 grams; and horses, 15 to 25 grams per day. With heavy rations of difficulty digestible foods, cattle may receive as much as 80 grams; sheep, 12 grams; and pigs, 15 grams per day. An excess of salt increases the consumption of water, and is undesirable. It is best to mix the salt with the food.

[1] See Ohio Bulletin No. 207.



A



B

Fig. 88.—Maud in her normal condition (A) and after nine months without salt (B). Wisconsin Station.

Phosphoric acid is found in the flesh. The animal takes up phosphoric acid when it adds flesh, and it gives off phosphoric acid when it loses flesh. Phosphoric acid is also found in the bones, as phosphates of lime and magnesia. Phosphates are also present in milk.

An animal which does not receive enough phosphoric acid, lime, and magnesia in its food, loses continually small quantities of phosphates of lime and magnesia. This is removed from its

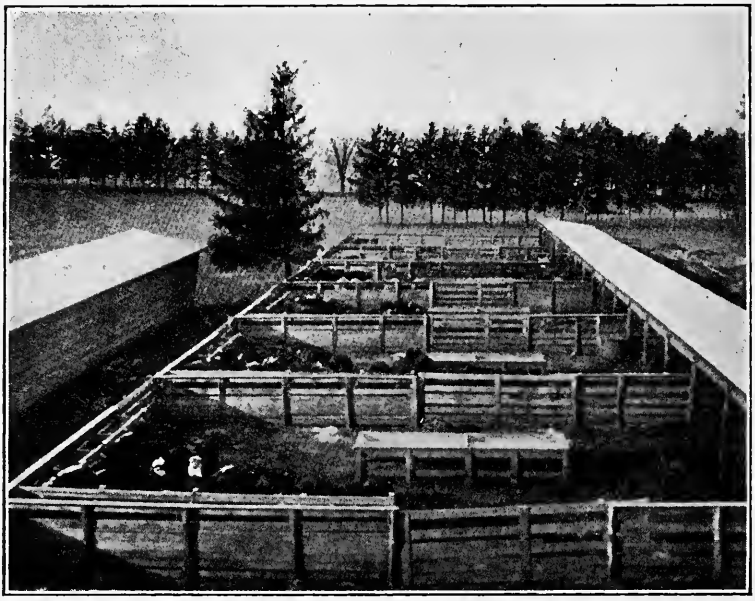


Fig. 89.—Pens used in feeding experiments. Illinois Station.

bones, making the bones porous, weak, and liable to break. This diseased condition occurs in some districts where the feeding-stuffs do not contain enough lime or phosphoric acid, and may be produced artificially by withholding phosphates from the animal. It may also be caused by an excess of acid in the food.

Growing animals which do not receive sufficient lime and phosphoric acid quickly suffer. Movement becomes painful to them,

the limbs and spinal column bend, the teeth remain small and loose, and the bones weak. Pigs especially are liable to suffer in this way because the potatoes and cereals fed to them do not contain enough lime.[1] Straw and chaff of cereals, the cereal grains, and their by-products, as bran, gluten meal, etc., malt sprouts, molasses, and whey, are poor in lime. The straw and chaff of grains, beet pulp, potato pulp, and molasses are poor in phosphoric acid. Clovers, meadow hay, and leguminous seeds are rich in lime. Cereal grains, bran, oil cake, flesh, and fish by-products are rich in phosphoric acid.

When lime is deficient in the feed, it may be supplied as precipitated chalk. Lime and phosphoric acid together may be given in the form of precipitated phosphate of lime or finely ground bone.

Lecithin[2] appears to stimulate the growth of the bones and body. For example, one guinea pig fed 0.10 gram lecithin per day, in addition to other food, increased 1,380 grams in 10 weeks; but another pig fed no lecithin, under the same conditions, gained 300 grams.[3]

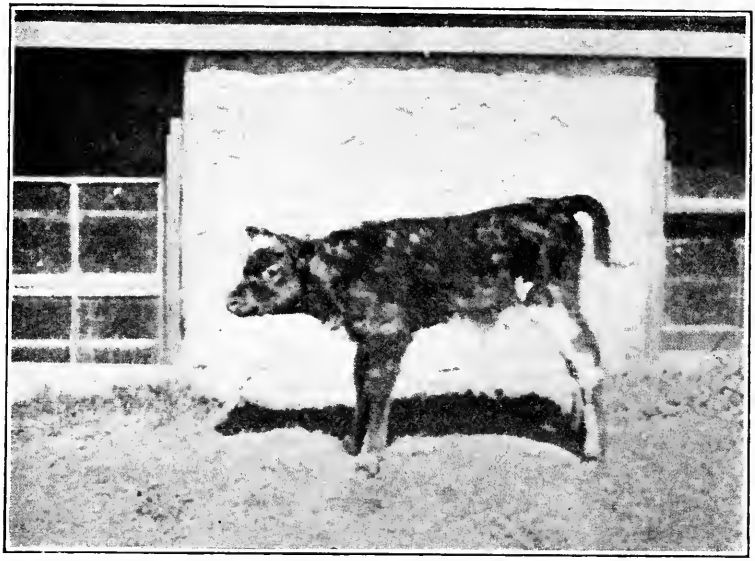
Water.—Water lightens the work of chewing, and makes swallowing possible. It is indispensable to digestion and absorption of food. The digestive ferments can act only in solution, and the products of digestion can enter the body in dilute solution only. Concentrated solutions cause strong peristaltic movements, which end with the ejection of the material. Water also circulates in the blood and secretions, and carries out the excreted metabolic products in the urine. It aids to remove an excess of heat from the body by evaporation. One gram of water on being converted from the liquid to the gaseous state takes up 535.9 calories.

Too little water delays digestion and absorption, and causes the nitrogenous metabolic products to remain in the body longer than usual. The blood gradually thickens, the body temperature is elevated, and the decomposition of fat and albumen con-

[1] See Missouri Bulletin No. 6.

[2] Missouri Bulletin No. 61.

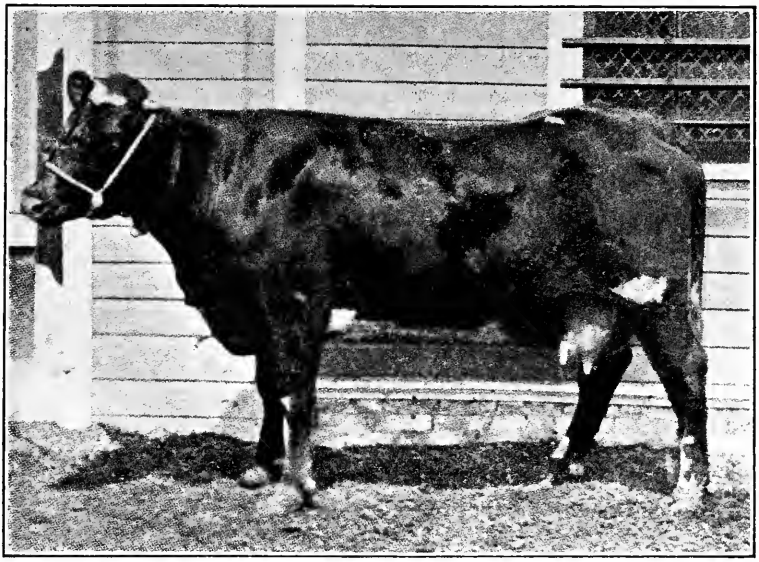
[3] Compt. rendu., 1902, p. 1166.



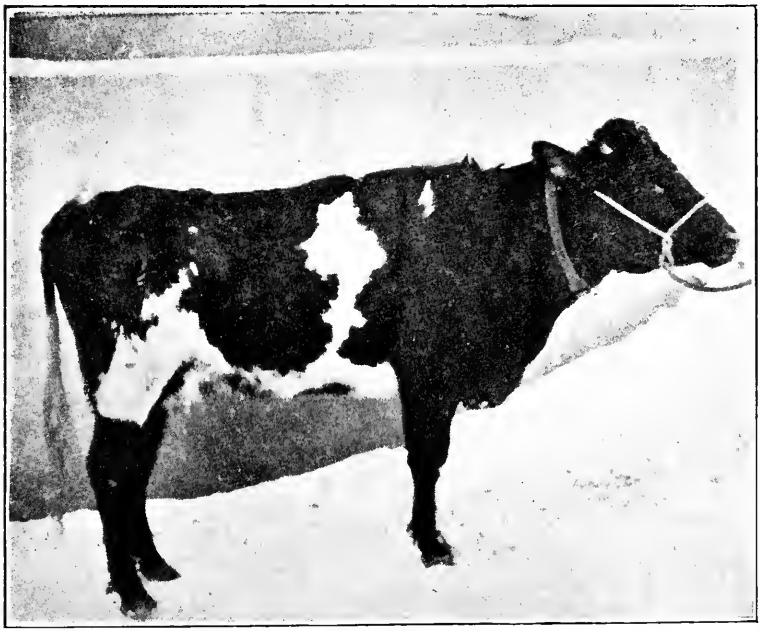
A

B

Fig. 90.—Calf (A) from cow fed on corn products, active at birth; calf (B) from cow fed on wheat products, unable to stand at birth. Wisconsin Station.



A



B

Fig. 91.—Cow (A) fed on corn products, vigorous; compare with cow (B) fed on wheat products, unthrifty. Wisconsin Station.

sequently increases. Growing animals are injured by too little water, or by receiving it at irregular intervals. When water is placed freely at the disposal of the animal, an excessive consumption is not to be feared, unless caused by very watery food or too much salt. The amount of water taken up on an average for one pound dry matter is as follows:

	Pounds
Swine	7 to 8
Cows	4 to 6
Oxen	2 to 3
Horses	2 to 3
Sheep	2 to 3

The quantity of water consumed varies with the temperature, as in warm weather more is required to replace that lost in perspiration.

Aromatic Bodies.—These are the bodies which give an agreeable taste and odor to feeding-stuffs. They have no effect upon digestion, and, on account of their small quantity, little on production. Their chief effect is upon the nervous system. They awaken the appetite, and increase the activity of the secreting organs of the mouth and stomach. Special additions of aromatics are not necessary when good hay, sound grain, by-products of milling, oil cakes, or even good stray or chaff is fed, for these contain in themselves sufficient appetizers.

Rations from Restricted Sources.—Experiments at the Wisconsin Experiment Station,[1] covering a period of four years, show that animals fed rations properly balanced, from different plant sources, were not alike in general vigor, size, and strength of offspring, and capacity for milk secretion. Animals fed from the products of the wheat plant exclusively were deficient in vigor; those fed from the corn plant were strong and vigorous; those fed from the oat plant were not as vigorous as those fed the corn plant; while those fed a mixed ration were intermediate between the wheat and oat rations in vigor. The significance of these investigations is not yet apparent.

[1] Research Bulletin No. 17.

CHAPTER XXI.

MAINTENANCE RATION AND FATTENING.

Maintenance Ration.—The amount of food required to maintain an animal is called the *maintenance ration.*[1] A maintenance ration must provide enough energy to keep up the body heat, and to supply the digestive and vital processes, and enough proteids to replace the body waste, and provide for natural growth of hair, horn, etc. The amount of body heat required will depend upon the surrounding temperature. At about 33° C. none will be required; the amount necessary at lower temperatures will depend upon the size and shape of the animal, its protective coverings, the quantity and temperature of the drinking water, etc.

Value of Food for Maintenance.—The quantity of body substance protected by given amount of food may be estimated as follows:

Determine the income and outgo of carbon and nitrogen of the starving animal. Feed the nutrient to be tested, and again determine income and outgo of the carbon and nitrogen. The amount of body fat and flesh protected by the known amount of nutrients fed is thus ascertained.

For example, the following is an experiment of Rubner:[2]

	Nitrogen eliminated per day	Fat decomposed per day
	grams	grams
Fifth and sixth day of hunger	3.16	75.92
Sixth and seventh day with meat	20.63	30.72
Increase +, or decrease —	+17.47	—45.20

The meat fed increased the elimination of nitrogen and decreased the destruction of fat.

The meat equivalent to 17.47 grams of nitrogen (=113.4

[1] Armsby, Bulletin No. 42, Pennsylvania Station.

[2] Zeitsch f. Biol., 1886, p. 04.

grams dry meat) protected 45.2 grams body fat from oxidation, so that 250 grams dry meat would protect 100 grams of fat. But the available energy of water-free meat is 404 calories; and that of dog fat is 940 calories, so that 100 grams fat has the same heat value as 232 grams of meat, and the meat protected body fat approximately in proportion to its available energy.

Similar experiments with sugar, starch, and other nutrients have shown that the value of different nutrients to an animal that is fed insufficient food are in proportion to their content of available energy. This is known as the *law of isodynamic replacement of nutrients*. This law holds only when the thermal energy of the food can be entirely utilized in maintaining the temperature of the body. When the thermal energy is of no value, as when the surrounding temperature is the same as that of the body, nutrients should replace one another only in proportion to their content of kinetic energy. (See Chapter XX). When the thermal energy is only partially utilized, the law is only partly true.

Carnivorous animals may be maintained on a ration consisting of flesh alone. The quantity necessary is between three and four times as much as that oxidized by a starving animal. An addition of fat, sugar, starch, or crude fiber decreases the amount of proteids required.

Ascertaining the Maintenance Ration.—The ration which will keep an animal without loss or gain of fat or flesh is termed the maintenance ration. The maintenance ration is ascertained exactly by feeding an animal on a given ration, and determining the loss or gain of flesh and fat by means of the carbon and nitrogen balance. The protein and non-protein in the ration are decreased, or increased, as appears necessary from the previous experiment, and the carbon and nitrogen balance again determined. That ration which produces only a very slight gain of flesh and fat is considered to be the maintenance ration. It is practically impossible to feed a ration which does not produce either a slight gain or loss.

Factors which Affect the Maintenance Ration.—The size of the maintenance ration is affected by several factors in addition to the vital needs of the animal.

External Temperature.—When the atmosphere has the same temperature as the animal body, no heat is required to keep the animal warm. The thermal energy of the food, produced in digestion, will maintain the animal heat for a few degrees below 33°, which will vary according to the character of the food. At lower temperatures, food must be oxidized to keep the animal warm. The amount of food so required will depend upon the temperature, and other factors. For example, Rubner[1] found the heat given off by a starving dog, is measured directly in a calorimeter, to be as follows:

Temperature Degrees C.	Heat evolved Calories
7.6	86.4
15.0	63.0
20.0	56.0
25.0	54.0
30.0	56.0
35.0	68.5

About 65 per cent. more energy was used at 7.6° C. than at 25°. At 35° the elimination of heat is increased, probably owing to disturbances due to the high temperature.

Feeding standards are based on a temperature of 15° to 20° C. At higher temperatures, less feed will be required, at lower temperatures, more. Since small individuals have a proportionally larger body surface than the large animals, they give off more heat, and so require more food. For example, it is estimated that a grown steer weighing 300 pounds would require per 100 pounds weight, food of 0.19 pounds fat value, while a steer of 800 pounds, requires per 100 pounds weight, food of 0.14 pounds fat value, or one-fourth less, weight for weight.

The Condition of the Animal.—The fatter the animal, the more food it requires for maintenance. The increased food required is not in proportion to the gain in weight, but the pro-

[1] Gesetz d. Energieverbrauch, 1902, p. 105.

portion is greater than the gain, and increases as the animal becomes fatter.

Temperature of Drinking Water.—Water consumed must have its temperature raised to the temperature of the animal body. That, of course, requires heat, the amount required being considerable if the water is cold. For an example, an ox weighing 1,000 pounds requires for maintenance, food having the productive value of 750 grams fat per day. Such an animal may consume 50 kg. water per day. If this water has the temperature of 5° C. the temperature must be raised to 39°, that is, 34°, and the heat required is 34 x 50 = 1,700 calories, which is equal to about 190 grams fat. This is about 25 per cent. of the maintenance ration. Cold drinking water must thus be compensated for by more feed.

Value of Protein for Maintenance.—Proteids alone will maintain the animal body. The quantity of proteids required is considerably in excess of the amount of body proteids oxidized by a starving animal. By experiments on dogs, starved, and then fed on lean meat, it has been found that for 100 parts body proteids oxidized, 369 parts proteids in lean meat must be consumed to maintain equilibrium.

The proteids in the body are in two forms, circulatory and body proteids. The circulatory proteids are rapidly oxidized, while the body proteids are much more resistant. Thus, the amount of proteids oxidized by a starving animal will depend at first upon the quantity of circulatory proteids in the animal, which in turn depends upon the quantity of proteids previously fed. The quantity of proteids oxidized while an animal is starving, rapidly decreases until it becomes nearly constant.

The amount of proteids destroyed the first day depends upon the previous ration, but after the fifth day it becomes nearly constant.

Ammonium acetate, asparagin, and other nitrogenous, non-proteid bodies, have little or no value for maintenance. An animal fed upon them, together with starch, fat, etc., will starve to death for want of proteids.

Value of Non-Protein for Maintenance.—Non-protein nutrients, such as sugar, starch, fat, etc., fed alone, will decrease the destruction of body proteids by a starving animal to a certain extent, but not entirely, and the animal will starve if so fed. A certain quantity of proteids is essential. The most practical maintenance ration is one which contains both protein and non-protein.

Feeding for Maintenance.—Work animals may be placed on maintenance rations during periods of idleness; fat cattle, between end of fattening period and time of sale; grown animals, until the time of fattening begins; and sheep kept for wool. Young animals, cannot be placed upon a maintenance ration, as a gain of flesh is the normal condition with them.

The maintenance ration must provide sufficient energy and sufficient proteids for replacement of flesh and fat, and the growth of hair, horn, skin, and hoofs. It must be adjusted to the size and condition of the animal, and other external conditions, such as we have discussed.

On account of the small quantity of kinetic energy and the relatively high amount of heat required for maintenance, and also because the feed should be bulky in order to satisfy the appetite of the animal without carrying large amounts of nutriment, hays and straws may be largely used.

Standards for Maintenance.—The following are the amounts of food found necessary for maintenance per day and per 1,000 pounds live weight:

	Total weight dry matter	Proteids	Productive value	Nutritive ratio
	pounds	pounds		
Steers	12–21	0.6–0.8	1.50	1 : 9
Sheep, coarse breeds	18–23	1.0	2.08	1 : 9
Sheep, fine breeds	20–26	1.2	2.25	1 : 8
Fat steers	21–24	1.0–1.50	1.75–2.25	1 : 8

These standards are based upon experiments such as those just cited. Sheep must receive enough protein to provide for growth of wool. Methods for calculating rations will be given in an-

other chapter. The nutritive ratio given in the table is the ratio of protein to non-protein, and not of *proteids*.

Coarse feeds are largely used for maintenance purposes. As they almost invariably contain enough phosphoric acid and lime to supply the needs of the animal, the ash needs little attention. Such an animal requires per 1,000 pounds live weight about 45 grams of lime and 22 grams of phosphoric acid in the food.

Utilization of Nutrients for Production of Fat.—The object of fattening the animal is to finish it for market. Some of the facts and principles upon which the fattening rations are based will be discussed. Only the food fed in excess of maintenance requirements may be used in fattening. In the preceding chapter, we not only had the evidence that proteids, crude fiber, fat, and nitrogen-free extract could furnish fat,[1] but also the quantity of fat which each could produce. Other methods of experiment have been used to ascertain whether the nutrients of the food may be used for the production of fat.

Hoffman[2] fed a dog (previously starved for some days) on 370.8 grams of fat, and 49 grams of proteids (lean meat) per day. In five days the animal gained 4.2 kilograms and then contained 1352.7 grams of fat. The amount of fat present at the beginning of feeding was estimated at 150 grams as ascertained by examination of the dog. The maximum quantity that could have been formed from the proteids fed was 130.5 grams. The remainder of the fat, at least 1,072 grams, must have come from the fat eaten.

The following experiments of Soxhlet[3] show that carbohydrates may form fat. Three pigs 5 to 6 months old were first fed alike for 321 days. One was killed then and the body subjected to analysis to ascertain its fat content. The remaining two were fed on steamed rice for 75 days and 82 days, respectively, the nutrients digested being determined by analysis of food and excrement as in digestion experiments. The animals

[1] Soskin, Exp. Sta. Record 8, p. 179.

[2] Landw. Versuchs-stat., 1894. p. 475.

[3] Centralblatt f. Agr. Chem., 1881, p. 574.

were then killed and subjected to analysis. A quantity of fat equal to that in the pig first killed was subtracted, and the difference assumed to represent the gain in fat. The results of the experiment are as follows:

	Pig No. 1	Pig No. 2
	kg.	kg.
Nitrogen digested	1.44	1.60
Nitrogen retained as flesh	0.89	0.45
Nitrogen in proteids decomposed	0.55	1.15
Fat possible from proteids decomposed (assuming proteids produce 51.8 per cent. fat)	1.78	3.68
Fat in food fed	0.30	0.34
Total fat possible from proteids and fat of food	2.08	4.02
Gain of fat by animal	10.08	22.18
Gain from carbohydrates	8.00	18.16

Thus, after allowing for the greatest possible gain of fat from the proteids and the fat fed, there remains a large quantity of fat which could come only from the carbohydrates.[1]

The fat of the animal has been found to be modified by the fat of the food to a certain degree. In one experiment, a fat containing iodine was fed, and was found in the body fat, and also passed into the milk. A portion of the fat of the food may be stored in the animal. The body fat of each kind of animal possesses characteristic properties; the cow produces only cow fat; the dog, dog fat, etc. Under ordinary conditions, only a small part of the animal fat comes directly from the food; the major portion is a product of the transformation of matter in the cells of the animal. Only when foods rich in fat, such as oil cake, corn, rice bran, etc., are fed, can the characteristics of the food fat be observed in the fat of the body or of the milk. It is usually the custom to finish the animal on feed which will give the desired characteristics. The fat of animals fed on cereals and grains rich in carbohydrates and poor in oils, is hard. A softer fat is obtained when linseed cake, peas, wheat bran, oats, etc., are fed. Animals exposed to cold have a softer fat than

[1] See also Bulletin 22, p. 271, Office Exp. Sta., U. S. Dept. Agr.

those kept in warmer surroundings. A pig kept in a pen at freezing temperature had a softer fat than similar pig kept in a pen at 30-35° C.

Composition of Gain of Weight in Fattening.—The composition of the increased weight in fattening has been studied in two ways:

First, animals of different degrees of fatness, but otherwise comparable, were killed and subjected to analysis.

Second, animals raised alike were selected, and some killed at the beginning, others at intermediate stages, others at the end of the fattening experiment. The bodies were subjected to analysis.

The animals killed at the end of the experiment or during the process, were supposed to have originally had the same composition as those killed at the beginning of the experiment. When the live weight of the animals and their percentage composition is known, it is a simple matter to calculate the composition of gain in material during fattening.

The composition of sheep at different degrees of fatness was found at Rothamsted[1] to be as follows:

PERCENTAGE COMPOSITION OF SHEEP.

	Lean	Half fat	Fat	Very fat
Offal				
Stomach and intestines	6.0	9.1	6.0	5.2
Carcass				
Proteids	14.8	14.0	12.2	10.9
Fat	18.7	23.5	35.6	45.8
Ash	3.2	3.2	2.8	2.9
Water	57.3	50.2	43.4	35.2
Total	100.0	100.0	100.0	100.0

It is noted that there is a decided decrease in the percentage of water, a slight decrease in the percentage of proteids, and a large increase in the percentage of fat, during the process of the fattening. With other animals than sheep, the results were similar.

The following table shows one calculation of the composition of the gain in fattening, and illustrates the method of procedure. The part of the offal in the gain is calculated also.

[1] Bulletin 22, p. 249, Office Exp. Sta., U. S. Dept. Agr.

COMPONENTS OF A FAT AND A LEAN SHEEP, SHOWING THE COMPOSITION OF THE GAIN IN FATTENING.

	Very fat kg.	Lean kg.	Gain kg.	Percentage composition of gain
Total weight	108.6	44.3	64.3	100.0
Proteids	11.83	6.56	5.27	8.2
Fat	49.74	8.27	41.47	64.5
Ash	3.15	1.41	1.74	2.7
Water	38.23	25.38	12.85	20.0
Offal	5.60	2.67	2.93	4.6

The average increase in body substance on fattening, exclusive of offal, from the experiments on oxen, sheep, and swine at the Rothamsted Experiment Station is as follows:

Proteids	7.5
Fat	66.6
Mineral matter	1.5
Water	24.4
	100.0

It is seen that the increase is mostly fat, only a small part being proteids. The nutritive ratio of this gain is 1 : 20. These animals were not entirely grown. Grown animals, if in fair condition, gain very little flesh (proteids) when fattened.

Factors which Influence the Fattening Ration.—A number of factors influence the fattening ration:

Requirements for Maintenance.—Since only the excess of the productive value of the food over the maintenance requirements may be used for fattening, anything which affects the maintenance requirements will affect the fattening ration. An increase in the maintenance requirements will decrease the gain in fat.

Stall Temperature.—On account of the heavy ration fed, the animal has a large excess of thermal energy, and the temperature of the stall may fall lower than when fed on a maintenance ration without affecting the amount of fat gained. But if the stall becomes too cold, maintenance requirements are increased and the animal gains less fat. If the animal has to warm the water consumed in cold weather to the body temperature, the maintenance requirements may be considerably raised. A large proportion of the material otherwise available for fat might be so used. It has

often been found profitable to warm the drinking water, especially for hogs.

If the external temperature is too high, the animal may have trouble in disposing of the heat from the excess of thermal energy, and will then eat less of the ration. For this reason fattening in summer may be difficult; in some parts of the South, animals fatten better when fed out of doors where the perspiration may evaporate freely, than when confined. It is also often advisable to feed light, rather than heavy fattening rations during warm weather.

Condition of Animal.—The fatter the animal, the more food required for maintenance, and the less the proportion of it available for fattening. Thus the cost of the production of fat increases with the duration of the fattening process.

Age of Animal.—South Dakota[1] experiments show the following relation between feed consumed and gain in weight, for cattle of different ages.

	Pounds eaten for each pound of gain in live weight	
	Concentrates	Hay
Yearling steers	6.7	4.3
Two-year-old steers	7.9	4.6
Three-year-old steers	8.5	5.1

Excess Over Maintenance Requirements.—Only the excess of food over the maintenance requirement can be used for production. The larger the excess, within the limit of the ability of the animal to use it, the more economically the food is used. For example, if a steer weighing 1,000 pounds that requires 1.5 pounds productive value for maintenance, is fed 2.0 pounds, then only 0.5 pounds, or one-fourth of the ration is used for production of fat. But this animal should be able to use 3.0 pounds productive value, and in such case 1.5 pounds, or one-half of the value of the food is used for fat. The fat produced by the first ration will require twice as much productive value as that formed by the

[1] Bulletin No. 125.

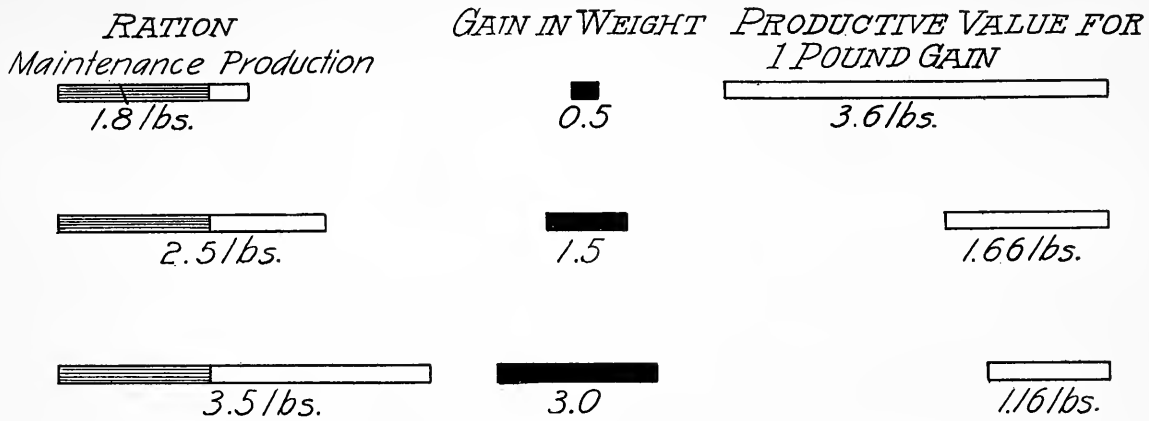


Fig. 92.—Relation of productive value of a ration to gain in weight, and cost of gain.

second. The second ration should produce the same results in two months that the first would give in five. In the latter case there is not only a greater expenditure for food, but also twice as long to feed and care for the animal.

This may be put in another way. Suppose a steer weighing 800 pounds is fed on 5 pounds cottonseed meal and 20 pounds cottonseed hulls per day. This ration would have a productive value of 1.55. The animal would have a maintenance requirement of 1.2, leaving 0.35 pound for fattening, which would produce about 0.5 pound gain in live weight per day. Suppose one pound corn meal is substituted for one pound cottonseed hulls. The ration would gain 0.17 pound in productive value, which should cause a gain of about 0.25 pound in live weight per day. An addition of 2 pounds corn meal would thus double the gain in weight per day.

Too heavy a fattening ration taxes the capacity of the animal, and decreases the production of fat. The excess interferes with the digestive processes and makes the fattening less successful. Experiments have shown that an excessive ration does not produce as large gains as a ration adapted to the capacity of the animal. The following are results of two series of experiments by Morgan[1] on sheep, in which the quantity of protein was kept constant, but the carbohydrates were increased. The effect of the increase in the ration is to *decrease* the gain in weight.

DIGESTIBLE NUTRIENTS FED PER 1,000 POUNDS LIVE WEIGHT.

	Protein	Carbohydrates	Daily increase in weight
	pounds	pounds	pounds
Experiment 1			
Group A	3.54	16.5	3.56
Group B	3.54	18.9	3.76
Group C	3.54	21.3	2.79
Experiment 2			
Group A	5.18	18.1	4.06
Group B	5.18	20.7	3.87
Group C	5.18	23.3	3.70

[1] Quoted by Kellner, Die Ernährung d. Landw. Nützture, p. 414.

Feeding Experiments.—The values of feeding-stuffs for fat production are often compared by means of feeding experiments. Feeding experiments have also been of great value in establishing standards of feeding for various purposes. Feeding experiments do not give such exact values as experiments in which the carbon and the nitrogen balance are determined, but they are very useful in their proper field.

Two systems of feeding experiments are used. In the first system, the same groups of animals are fed upon the different rations in succession. The method is open to the objection that the effect of any ration will depend to a considerable extent upon the preceding rations, and the same feed may give entirely different results according to the character of the feeding which precedes it. The feed, of course, affects the condition of the animal, so that the maintenance requirements vary, and the excess of the ration over the maintenance requirements, which is the portion used for the gain in weight, will depend upon the previous feeding. The results of the feeding will thus depend upon the previous feed, as well as on the ration being studied.

The second system consists in dividing the animals into groups, and feeding to the different groups the rations to be compared. This method gives good results when properly used. Care should be exercised to have the groups exactly equivalent at the beginning of the test. The groups should consist of 10 or more animals. Each animal should be matched in age, form, live weight, etc., with another animal in the other group. The groups should be compared by means of a preliminary feeding period, in which the animals receive the same ration for thirty days or more. If each group makes the same gain on the same feed, the experiment proper may be begun; but if there is only a slight difference in gain, the groups should be rearranged, and another test made.

The best results are secured when the ration is about three quarters of the standards. If the production is forced to its upper limit, or if more feed is given than the animal can utilize, the differences, due to the different feeds, may be insignificant.

When different feeds are added to a basal ration, the productive value should not be altered by other compensatory additions. For example, if cottonseed meal is compared with gluten meal, and straw is added to increase the nitrogen-free extract for cottonseed meal, the experiment would be unfavorable to cottonseed meal, because the nitrogen-free extract of straw is not equal to that of gluten meal. The rations should be weighed out for each animal, and fed in such order or with such preparation that they will be completely consumed.

The live weight varies very much on account of irregular excretion of dung, irregular elimination of urine, unequal consumption of water from day to day, etc. The animals should be weighed three days in succession, just before the midday meal, every ten days. Since the first weighings are usually of little value, on account of the animals being excited, the animals should be accustomed to the weighing as early as possible.

The feeding period should not be too short. Two months is the minimum for fattening and work animals, but it is better to continue the experiment with fattening animals, until they are fully fat and then to make a slaughter test on them. Important observations are sometimes made only when the experiment is continued a long time.

When comparing two feeds, equal quantities should be fed. If one feed is more palatable than the other, and the animals allowed to eat more, they will have a larger excess over their maintenance requirements, and the results will be more favorable to the more palatable food.

Standards for Fattening Rations.—Since fattening animals put on little flesh, it would appear that they require little more proteids than animals on a maintenance ration. The heavy ration fed, however, demands a quantity of digestive fluids composed largely of proteids. Since the digestibility of the food is decreased if the nutritive ratio is too wide, the nutritive ratio should not be wider than 1 : 10. A ratio narrower than 1 : 4 increases the oxidation of matter in the body, and so decreases the production of fat. Numbers of experiments have been made

comparing wide and narrow rations. Wolff,[1] for example, taking the average of 18 experiments, found sheep to make equal gains whether the nutritive ratio was 1 : 7 to 8, or 1 : 4 to 5. Lehmann[2] compared 1 : 12 to 1 : 5, with equal results. There is thus a wider margin in the quantity of digestible protein which may be fed, and if protein is sufficiently cheap, it may be used for the purpose of producing fat.

If the animal is not in good condition, the ration should be moderate at first and gradually increased, beginning with a nutritive ratio not wider than 1 : 6.

The quantity of fat fed is not important, but if fed to ruminants in greater quantity than one pound per 1,000 pounds live weight, it is liable to decrease the appetite or cause digestive disturbances and interfere with the fattening. Pigs can use more than this amount.

The fattening ration for steers should not exceed 3.6 pounds productive value per day and per 1,000 pounds, but may be lower than this, according to the time it is desired to take for the fattening. Rapid fattening is less expensive than slow fattening. The increase in live weight in fattening diminishes in the course of the process, since the maintenance requirements increase with the increase in weight of the animals. The cost of production of gain in weight increases considerably towards the end of the fattening period.

The following are the amounts of nutrients desirable for fattening, per day and 1,000 pounds live weight:

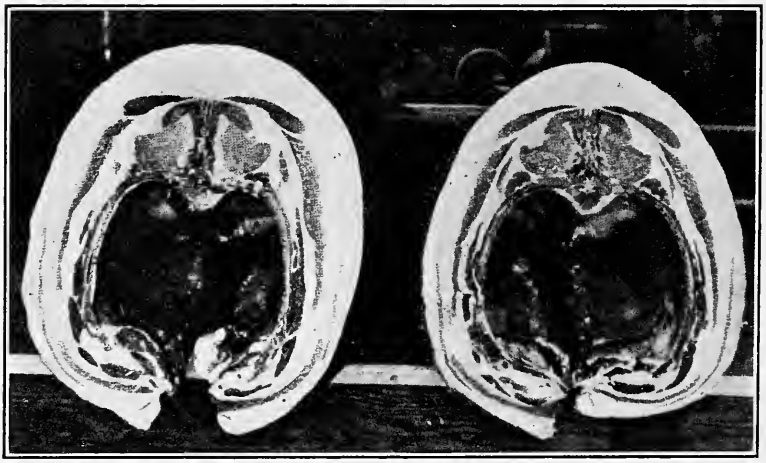
	Total weight dry matter	Proteids	Productive value	Nutritive ratio
Pigs				
Preliminary period	33–37	3.0	6.8	1 : 5.5
Fattening period	28–33	2.8	6.5	1 : 6.0
Final period	24–28	2.0	5.0	1 : 6.5
Fattening sheep	24–32	1.6	3.6	1 : 4.5
Fattening oxen				
Preliminary period	22–30	1.8	3.0	1 : 6.4
Main period	24–32	1.6	3.0–3.6	1 : 5.5
Finishing period	22–30	1.4	2.8–3.4	1 : 6.0

[1] Landw. Jahrbuch, 1896, p. 193.

[2] Landw. Jahrbuch, 1902, p. 162.

The *fattening standard* calls for that quantity of feed which gives the most rapid fattening. Any excess of feed over the maintenance requirements produces fat; the fattening standard gives the largest quantity which should be used.

Practice of Fattening.—Straw has little value for fattening purposes. It is so bulky that the animal cannot eat sufficient feed for best results, when the straw is used in quantity in the ration. Even good meadow or clover hay has too great bulk in proportion to its nutritive content to be used in quantity in intensive fattening. Good pasturage is excellent for fattening, and in exceptionally favored localities may be the only fattening feed. But usually the animal is finished on more concentrated feed.



A B

Fig. 93.—Carcass of hogs fed on, (A) corn and, (B) barley. North Dakota Station.

In feeding large rations, care must be taken to render the food palatable, so that the animal will be induced to eat as much as possible. The use of well-flavored feeds, salt, molasses, or special preparation of the feed, may be of advantage in causing the animal to consume the desired amount.

Anything that disquiets the animal, as irregular meals, rough treatment, insufficient bedding, etc., increases the oxidation of matter and decreases the production of fat. Armsby has found, by direct measurements, that an animal standing consumes about one-fourth more energy than when lying down. The temperature of the stall should be kept low rather than high, as the digestive processes of the fattening animal evolve a considerable amount of heat, which is partly radiated and partly carried off by evaporation of water from the body. If insufficient ventilation, heavy hair, or fat layers under the skin decrease evaporation, the animal instinctively consumes less food.

The effect of fattening is chiefly perceptible in increase of live weight. At the beginning, the weight increases rapidly for a few days, due to filling the body with food and water. After the fattening proper has been begun, regular weighings, which are best made before the morning meal, shows the progress of the fattening. According to the quantity of the feed, a tolerably constant increase in weight occurs for a longer or shorter period. The weekly increase then gradually becomes less and less, until finally it disappears. When the increase of weight ceases, it does not prove that fattening has ceased. Fat continues to be deposited for a time, taking the place of water, until the capacity of the tissues is satisfied. The cost of production of the increase of fat and flesh increases considerable towards the end of the fattening period.

Another cause of the decreased production with length of fattening period is the increase in the maintenance requirement of the animal, which takes place more rapidly than the increase in weight.

For the maintenance of fattening animals, rations much smaller than the fattening ration suffice, and should depend on the degree of fatness. The transition to a maintenance ration should be gradual.

Hogs 1-½ years old require no specially high amounts of protein. As they have a high digestive power for carbohydrates the nutritive ratio may be as wide as 1 : 10.

Excessive quantities of fat in the feed may injure the quality of the bacon. At the beginning of the fattening period, hogs may consume as much as 30 pounds food per 1,000 pounds weight, but as the fattening progresses, which ends in 3½ to 4 months, the consumption of food sinks considerably, until towards the end, 19 to 20 pounds are used. The ration for the different periods of fattening are shown in the table previously given.

If the hogs are in poor condition, a preliminary period of 2 to 4 weeks with 4 pounds proteids is advisable. The proteids should also be increased if the animals are not fully grown.

CHAPTER XXII.

FEEDING WORK ANIMALS AND GROWING ANIMALS.

Work requires energy, which is produced by the oxidation of organic matter within the tissues. It has been known for a long time that animals use up more oxygen and give off more carbon dioxide while they are doing work than when they are at rest. A considerable amount of investigation has been required to ascertain the value of different nutrients for producing work.

Nutrients Oxidized During Work.—The effect of work upon the proteids of the body can be studied by determining the quantity of nitrogen in the urine during periods of rest and periods of work. If the work necessarily involves a destruction of proteids, an increased elimination of nitrogen will result. Experiments have given contradictory results. For example, a dog fed on meat eliminated the following quantities of nitrogen, during three consecutive periods:

	Nitrogen in urine grams per day
No work	54.9
Working	48.6
No work	55.0

In other experiments, the proteid metabolism was considerably increased. The results depend on the ration being fed. If the ration supplies sufficient carbohydrates and fat to furnish energy for the work, proteids will not be oxidized, but if the ration is deficient in this respect, proteids will be oxidized to furnish the necessary energy.

Animals at work exhale increased amounts of carbon dioxide, even though there be no increase in the quantity of nitrogen eliminated. This is evidence that fats or carbohydrates are being used for the production of work. Further evidence that starch and other non-proteids can be used for the production of work, is afforded by experiments, such as the following:

A working animal was fed on a ration poor in protein. In a second period the same ration was fed with the addition of starch and the amount of work was then increased until the

same amount of nitrogen was eliminated as in the first period. When the same amount of protein was being decomposed, it was found that the animal was doing more work. That is, the starch was used for production of work. A similar experiment showed that oil enabled the animal to do more work. An experiment showing that proteids may be used in work was as follows: A horse was fed a ration rich in protein, and put on light work for about ten days. The work was then trebled, being a hard day's work. The excretion of nitrogen immediately increased 45 grams per day, and the live weight of the animal gradually decreased.

Exercise may cause muscular growth. For example, Atwater and Benedict found that a man at rest lost 0.7 gram nitrogen per day and 7.8 grams fat; but when working, he gained 1.1 gram nitrogen and lost 48.4 grams fat on the same ration.

Respiratory Methods.—The following is a method[1] for determining the consumption of energy during various kinds of work, which has also been of service in other studies, such as ascertaining the amount of energy involved in chewing. The animal to be studied is subjected to a surgical operation, and a tube inserted into its windpipe, so that while air may be inspired freely, the expired air passes through a rubber tube into a suitable vessel for collection. The expired air is measured, and the quantity of carbon dioxide and oxygen in it determined. The quantity of nitrogen eliminated in the urine is also determined, and shows how much proteids have been oxidized. When fats are burned, for every 1 cc. of oxygen which disappears, 0.707 cc. carbon dioxide is formed. With carbohydrates, 1 cc. oxygen is replaced by 1 cc. carbon dioxide. Hence the ratio of carbon dioxide to oxygen (corrected for proteids consumed) allows us to calculate the relative proportions of fats and carbohydrates oxidized. This method cannot be considered as highly accurate. By means of it, the expenditure of energy caused by walking or running on a smooth slope, going up-hill, drawing a load, etc., have been studied.

[1] Hagemann, Exp. Sta. Record 10, p. 813.

Energy for Work.—Work is measured in meter-kilograms, or foot-pounds. A meter-kilogram is one kilogram raised to the height of one meter. Exact experiments have shown that one large calorie, if completely transformed into kinetic energy, can perform 425 meter-kilograms work. Experiments have shown that an animal can utilize for work about one-third of the *available* energy in the food. In ten experiments on a man climbing stairs, the percentage was 33.1 per cent., and in eighteen experiments on a horse, it was 29 to 38 per cent. It is estimated by Kellner that, after allowing for all losses, 1 gram of pure protein digested will yield 656 meter-kilograms work, 1 gram of fat 1,214, and 1 gram of carbohydrate, 533. The rate of work, and the kind, both affect the consumption of nutrients, also the shape of the animal as related to the kind of work done. Being accustomed to a particular kind of work also decreases the oxidation of nutrients. It is said that a man working a treadmill oxidized 25 per cent. less nutrients after 56 days work, though doing the same quantity of work per day. According to the structure of the working animal, the development of its muscles, and the position of the extremeties doing the work, the portion of the energy which appears in the work varies. For moving their own bodies, Zuntz found a variation of 0.284 to 0.441 calories per 1 kilogram weight and 1 meter distance with different animals. Fatigue increases consumption of energy.

Rations for Working Animals.—Animals when at work require little more proteids than when not at work; a nutritive ratio of 1 : 7 is sufficient.

Horses will work off nutrients fed in excess of the maintenance ration by increased movements in the stall, so that it is not possible to assume that the maintenance ration is secured when an equilibrium between income and outgo is secured.

Standards for Work Animals.—Two methods are used for studying the needs of working animals. One is to determine the maximum amount of work which can be secured with a given ration without loss of condition. The other method consists in

starting with an insufficient ration, and gradually increasing it until it is sufficient to maintain the animal under the required conditions. Both these methods have been used to a considerable extent for studying the rations for working horses.

The following are standards for working animals, per day and 1,000 pounds live weight:

	Total weight dry matter	Proteids	Productive value	Nutritive ratio
		Pounds	Pounds	
Horse, light work	18–23	1.0	2.3	6.9
Horse, moderate work	21–26	1.4	2.9	6.9
Horse, heavy work	23–28	2.0	3.8	6.2
Ox, light work	20–25	1.1	1.9	10.9
Ox, moderate work	22–28	1.4	2.4	7.5
Ox, heavy work	25–30	1.8	3.2	6.0

A working animal can utilize somewhat more fat than a fattening animal.

Feeding Horses.[1]—In some large horse establishments only oat or wheat straw are used, as fewer cases of colic occur than when hay is used. Oats, barley, and corn are used for concentrates, oats being preferred in northern climates and corn in southern. Corn appears to be equally as good as oats. Care should be taken that the food is not musty or damaged, and horses should be allowed 2 to 2½ hours for eating and rest.

Growing Animals.—Growth is the normal condition of a young animal. Equilibrium between income and outgo would be an abnormal condition, if it could be secured.

With proper food, young animals gain in weight much more rapidly than mature animals with the heaviest fattening ration. The animals do not have smaller maintenance requirements, but they eat more in proportion to weight, and are able to store a greater excess over their maintenance requirements, than grown

[1] See Bulletin 125, Office Exp. Sta., U. S. Dept. Agr.

animals. A calf two to three weeks old has been known to retain 73 per cent. of the proteids consumed. As the animal grows older, the percentage of the food retained in the body decreases. The proportion of food eaten to live weight also decreases; thus, a larger proportion of the food must be used for maintenance.

The following experiments of Weiske[1] were begun with lambs four months old, and carried out in 7 periods of 1½ months each. The nutritive ratio was 1 : 4.6 at first and later, when about 15 months old, was 1 : 6.3.

PER 50 KILOGRAMS LIVE WEIGHT.

Period	Fed		Daily gain		
	Dry matter	Protein	Live weight	Nitrogen	Lime
	Grams	Grams	Grams		
I	1,101	188	363	6.75	3.20
II	1,073	163	271	5.16	3.76
III	917	139	206	3.71	3.65
IV	901	138	153	4.37	3.17
V	809	119	86	3.06	2.50
VI	762	108	63	2.94	2.63
VIII	733	98	85	3.77	2.64
IX	572	61	—	1.84	0.57

The quantity of food per 50 kg. weight consumed, decreases with the age of the animal, and the gain in weight decreases much more rapidly. Thus, the food eaten in the 8th period is 7/11 of that in the first, while the gain is only ¼.

The increase in weight of young animals is largely flesh, body organs, and bones. They thus require considerable protein. Young animals also require more mineral matter than older ones, to build up the bones. Lime and phosphoric acid especially are required. The preceding table shows the decreased retention of lime with age of the animal.

The following data compiled by Henry from the results of a number of feeding experiments with pigs at various Experiment Stations, shows the increase in the quantity of food required for a pound of gain as the animal grows older:

[1] Landw. Jahrbucher, 1880, p. 205.

Weight pounds	Feed eaten per 100 pounds gain pounds
15– 50	293
50–100	400
100–150	437
150–200	482
200–250	498
250–300	511
300–350	535

Mineral Matter.—Growing animals retain from 40 to 60 per cent. of the lime and phosphoric acid in the food. As the skeleton of a calf a year old contains on an average 17 pounds lime and 15 pounds phosphoric acid, the animal must take up 21 grams lime and 19 grams phosphoric acid per day, and the food should contain 40 to 60 grams each of these to meet the requirements. The body of a pig contains about 1.15 per cent. lime and 1.10 per cent. phosphoric acid, which would be equivalent to a daily increase of 3.8 grams lime and 3.7 grams phosphoric acid for a pig a year old weighing 250 pounds. As about 3 grams must be present in the food for 1 gram stored up, the animal will need 12 grams per day each of lime and of phosphoric acid. It is important to pay attention to the mineral matter in the food of growing animals.

Feeding Young Animals.—Animals intended for fattening should be fed more liberally than those that are to be used for milk or work. But with all animals the natural development should proceed normally. It is a serious mistake to assume that improper feeding when young can be counteracted by liberal feeding afterwards. Young animals fed with a deficiency of proteids yield a carcass of poor quality overcharged with fat.

The extreme sensitiveness of young animals requires care in avoiding all injurious influences, in food, as well as in care and protection. Food should be supplied often on account of the limited capacity of the animal. Regular feeding, clean vessels for eating and drinking, good care of the skin, a well ventilated stall, and clean, dry bedding are requisites to satisfactory growth. Drafts, cold, and wet, which affect young animals much more than old ones, are often very injurious. Sufficient exercise is neces-

sary for the full development of bones and muscles, and increases the resistance to adverse influences of weather and disease.

Calves.—Calves should be allowed mother's milk for the first few days. Calves intended to be used as milch cows should receive daily 1/7 to 1/8 of their live weight of full milk, for at least three weeks. Animals to be used for fattening should receive daily 1/5 to 1/6 of their weight of milk for about six weeks. Fresh milk, while still warm, is best. Ten liters milk or 1.2 kilograms solids produce about 1 kilogram live weight increase. The increase is, of course, proportional to the excess over the maintenance requirements and not to the live weight.

Other food should be introduced gradually. Skim milk may replace the full milk gradually, replacing the fat lost in skimming by a paste made of linseed or oat meal, 25 to 30 grams, to ½ liter of milk. Later linseed cake, bran, etc., may be used. Sour milk should be introduced gradually.

Calves have only one stomach and can utilize only easily digestible food. As they grow older, other stomachs develop and they can then use hay, etc. The animal gradually becomes accustomed to hay. At the end of the third month, beets, straw, softened oats, barley or pea meal, oil meal, malt germs, etc., may be fed.

When milk alone is fed, an addition of about 15 grams of precipitated chalk per day has been found beneficial. There is seldom a deficiency of phosphoric acid, but if straw and much grain is fed, there may not be enough lime in the food.

Lambs.—Lambs are usually weaned from 3 to 4 weeks after birth. Good meadow hay, and soaked oats, are fed and not too cold water. They should be allowed to suck often, at first. Sudden changes from stall to pasture are injurious. Lambs thrive on pasture. They require stronger food than calves.

Swine.—Pigs suck 6 to 8 weeks, but when 2 to 3 weeks old they begin to eat. They may be given unground barley or wheat grains or soaked oats, also some wood charcoal, hard coal, earth or sand. After three weeks, whole cow's milk heated and diluted ½ with water, may be fed. Milk and grain contain enough phosphoric acid, but not enough lime. It is well to add some pre-

cipitated chalk to the ration, which should be increased gradually from 8 to 10 grams per day.

Experiments have shown that a nutritive ratio of 1 : 4 is best until the pigs are 5 months old, as it gives the greatest increase of live weight for the food consumed. After this age, the ratio 1 : 6 is better.

Standards for Growing Animals.—The following are standards for feeding growing animals:

PER DAY AND 1,000 POUNDS LIVE WEIGHT.

	Pounds Total	Proteids pounds	Productive value pounds	Nutritive ratio
(I) Growing cattle, for milk cows or work:				
Age 2– 3 months	23	3.4	4.6	4.6
" 3– 6 "	24	2.8	3.7	4.9
" 6–12 "	26	2.3	3.1	6.0
" 12–18 "	26	1.8	2.6	7.0
" 18–24 "	26	1.3	2.3	8.0
(II) To be fattened:				
Age 2– 3 months	23	4.5	4.9	4.4
" 3– 6 "	24	3.5	4.3	4.6
" 6–12 "	26	2.8	3.6	5.5
" 12–18 "	26	2.2	2.8	6.5
" 18–24 "	26	1.5	2.5	7.5
(III) Growing hogs, to be fattened:				
Age 2– 3 months	44	6.2	8.5	4.0
" 3– 5 "	36	4.5	8.0	5.0
" 5– 6 "	32	3.5	6.6	5.5
" 6– 8 "	28	3.0	6.1	6.0
" 9–12 "	25	2.4	5.0	6.5
Growing hogs, for breeding:				
Age 2– 3 months	44	6.2	8.5	4.0
" 3– 5 "	36	4.0	6.8	5.0
" 5– 6 "	32	3.0	5.8	5.5
" 6– 8 "	28	2.3	5.0	6.0
" 9–12 "	25	1.7	3.9	6.5

CHAPTER XXIII.

FEEDING MILK COWS.

Milk cows are fed for the purpose of producing milk or butter fat. It was formerly believed that milk is extracted directly from the blood of the cow. But casein and milk sugar, which are constituents of the milk, cannot be extracted from blood, because they are not present in blood. Apparently, milk is elaborated from the blood and lymph by chemical changes within the cells of the udder.

Factors which Influence Milk Production.—A number of factors influence the quantity and composition of the milk.

Breeds of Animals.—Milk cows are divided into two groups of breeds, those giving relatively large quantities of milk with moderate fat content, and those giving less milk with a higher percentage of fat. To the first group belong the Holsteins, Ayrshires, Durhams, etc., and to the second, the Jersey and Guernsey. The average by König of about five hundred analyses of milk from animals belonging to these two groups, is as follows:

	Holstein group	Jersey group
	per cent.	per cent.
Water	87.49	86.83
Proteids	3.47	3.30
Fat	3.46	4.07
Sugar	4.86	5.04
Ash	0.72	0.76

Individuality.—Individuals of the same breed vary decidedly in the quantity and composition of the milk they give. For example, a study of each individual in a herd of 16 cows by Hitscher, showed the following differences:

	Minimum	Maximum
Duration of period of lactation	270 days	390 days
Total production of milk	2,330.0 kg.	4,702.0 kg.
Total production of fat	74.4 kg.	149.3 kg.
Percentage of fat in milk	2.63	3.81

The best cow gave twice as much fat and milk as the poorest. Some cows are very profitable, while others are fed at a loss. It is important to test the individuals of a herd; the unprofitable animals should be sold, and the feed of the others adjusted to the quantity of milk produced.

Fluctuations.—The amount and composition of the milk from the same cow may vary considerably from day to day. Thus, Fleischmann[1] found by daily measurement and analysis, that the amount and composition of the milk from the same cow, varied as follows:

	Total quantity of milk	Percentage of fat in milk
April	Kilograms	
Minimum	10.4	2.76
Maximum	12.1	3.46
Average	11.2	3.03
May		
Minimum	8.7	2.62
Maximum	13.7	3.93
Average	11.9	3.20

The table shows a variation of nearly 25 per cent. between the maximum and minimum for April, and 50 per cent. for May. The milk from the other cows in the herd varied also, but not on the same days, showing that the variations were not due to factors which influenced the entire herd alike, but to individual differences.

Period of Lactation.—The amount of milk given decreases with the time the animal has been giving milk, but the decrease varies with the animal. With some cows the decrease is regular and gradual, others give the same quantity for a long time and then suddenly fall off. The following table from Fleischmann's experiments, shows how the milk may decrease with period of lactation, and it also shows that the percentage of fat increases. Cow No. 1 behaves somewhat differently from

[1] Landw. Jahrbuch, 1891.

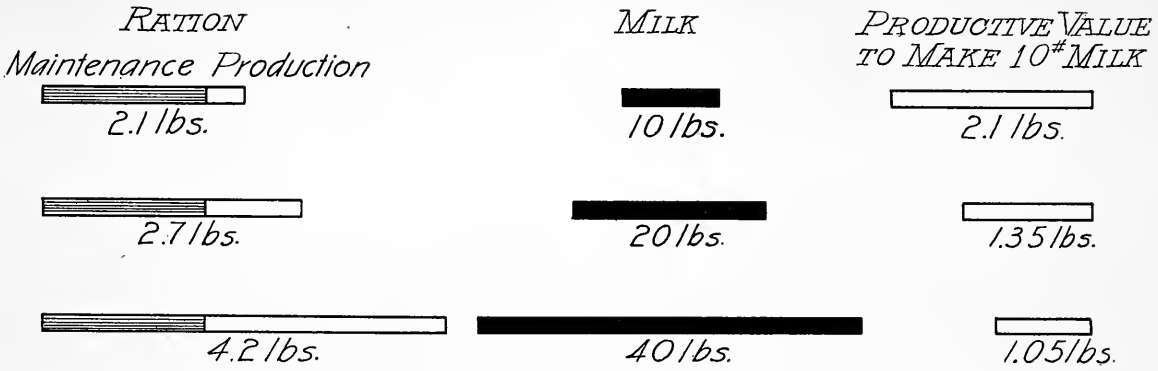


Fig. 94.—Relation of the productive value of a ration to the production and cost of milk.

cow No. 2, the decrease with the period of lactation taking place more regularly.

EFFECT OF PERIOD OF LACTATION ON QUANTITY AND COMPOSITION OF MILK.

	Average quantity of milk per day		Average percentage of fat in milk	
	Cow No. 1	Cow No. 2	Cow No. 1	Cow No. 2
April	11.6	14.4	3.0	3.5
May	12.0	15.9	3.3	3.1
June	10.5	16.6	3.4	3.0
July	8.8	12.8	3.5	3.2
August	9.7	12.9	3.6	3.3
September	9.1	10.5	3.7	3.6
October	7.7	8.5	3.4	3.4
November	6.6	6.7	3.8	3.5
December	5.1	5.6	4.3	3.8
January	2.2	2.8	5.8	4.7

Age.—The quantity of milk appears to increase slightly up to the fifth calf, and then decreases slightly. The fat content appears to remain constant for a long time.

Frequency of Milking.—The more frequently the cow is milked, the greater the quantity of milk, provided the milking is not done so often as to irritate the udder. This is shown by the following experiment of Kaull:[1]

Period of milking	Milk per milking	Milk per day
	kilograms	kilograms
Every 12 hours	3.81	7 6
Every 6 hours	2.46	9.8
Every 4 hours	2.06	12.4
Every 65 minutes	.66	14.6
Every 50 minutes	.07	14.1

As the udder fills, the formation of milk decreases. There is,

[1] Ber. d. Landw. Inst., Halle, 1891.

however, a tendency for the capacity of the udder to adjust itself to the quantity of milk produced by the cow. According to Fleischmann, from 6 to 7 per cent. more fat and milk are secured by three milkings instead of two. The number of milkings should depend upon the cost of the milking and the value of the milk. Four milkings may sometimes be justified with fresh cows of high productiveness, but under ordinary conditions not more than three, and often only two should be made.

The shorter the periods between milking, the richer the milk in fat and solids. Thus, when three milkings were made, the composition of the milk was found to be as follows in an experiment by Fleischmann:

COMPOSITION OF MILK.

	Dry matter	Fat
	per cent.	per cent.
4.00 A. M. milking	11.51	2.79
12.30 Noon milking	11.79	3.05
7.00 P. M. milking	12.44	3.76

Portion of the Milking.—If milk is gathered in fractions, and subjected to analysis, the first portions are found to be poorer in fat and solids than the succeeding portions. The following results were secured by Boussingault:[1]

COMPOSITION OF SUCCESSIVE FRACTIONS OF MILK.

	Weight of fraction grams	Percentage of dry matter	Percentage of fat
Fraction No. 1	398	10.47	1.70
Fraction No. 2	628	10.75	1.76
Fraction No. 3	1,295	10.85	2.10
Fraction No. 4	1,390	11.23	2.54
Fraction No. 5	1,565	11.63	3.14
Fraction No. 6	315	12.67	4.08

Not only are the strippings very rich in fat, but any milk left in the udder decreases the amount secreted. Hence all the milk possible should be removed at each milking.

[1] Ann. Chim., et Phy., 1866

Work.—Working the cow decreases the quantity of milk and fat produced, while the percentages of protein, fat, and ash increase. The effect depends upon the amount of work and the feed of the animal. Light work does not appear to decrease the total production of dry matter.

Palatability of Food.—It has been found that palatable food increases the yield of milk. In experiments in which two rations equal in feeding value were fed, the one tasteless, the other of well flavored hay, etc., the second ration always gave better results than the first.

Other Conditions.—The milk secreting organs are closely related to the nervous system. Rough treatment, disturbances, insufficient bedding, a cold stall, and other similar conditions decrease the quantity of milk and fat produced.

Methods of Investigation.—In studying the effect of various conditions upon the production and composition of milk, it is necessary to eliminate the influence of all factors except the one to be studied. Some of these factors, such as the kind and frequency of milking, may be eliminated by treating the animals alike. Others, such as individuality, may be compensated for by taking a sufficient number of animals. Two systems of experiment[1] are in use—the period system, and the group system, which correspond to the methods used for feeding experiments on fattening animals.

The Period System.—Ten or more cows are fed upon a standard ration for a period of two or three weeks. Next the cows are fed on the rations to be tested during three periods or more of the same length. The standard ration is then fed for another period. In each period, the production of milk and fat is determined. From the production of fat and milk during the first and the last periods, we calculate the quantity which should be produced during the intermediate periods, assuming that a regular decrease in production takes place. We compare the calculated production with that actually found to occur, and the difference gives the effect of the ration we are testing.

[1] See Kellner, Ernährung d. Landw. Nutztiere, p. 500.

For example, suppose the results with the standard ration during the first and fifth period of 20 days each, are as follows:

First period, average	14.27 kg. milk and	4.38 grams fat per day
Fifth period, average	13.63 kg. milk and	4.22 grams fat per day
Decrease	0.64 kg.	0.16 kg.

From the middle of the first to the middle of the fifth period is 80 days, or four periods. The decrease is thus 0.16 kg. milk and .04 grams fat for each period, and if the same ration were continued, the daily production for each period should be:

Period 1 (found)	14.27 kg.	milk and	4.38	grams	fat	per day
Period 2 (calculated)	14.11 "	"	4.34	"	"	
Period 3 "	13.95 "	"	4.30	"	"	
Period 4 "	13.79 "	"	4.26	"	"	
Period 5 (found)	13.63 "	"	4.22	"	"	

The actual production with the ration being tested during the intermediate periods is compared with the calculated production. For example, if the production is 13.00 kg. milk and 4.10 grams fat in period 2, the ration fed has decreased the production 1.11 kg. milk and 0.24 grams fat.

This method assumes a regular decrease in the production during the period of lactation. This assumption may or may not be true with one or two animals, but with eight or ten cows, it is practically true.

The difference in the condition of the animal due to the previous feeding also has some effect upon the quantity and quality of the milk.

Group System.—This corresponds to the group system for fattening experiments. Each cow should be matched in race, age, weight, period of lactation, quantity and composition of milk against similar animals in the other groups. The groups are fed alike for a preliminary test period of 30 to 60 days, during which the yield and composition of the milk is estimated. If any differences in the groups appear, the cows should be rearranged, or new animals brought in, and another test made. When each group makes the same production with the same ration, the ex-

periment is begun. The composition and quantity of the milk is then determined for a period of ten days. A test period follows in which the feeds to be tested are compared. One method of procedure is as follows: Suppose Indian corn and Kaffir corn are to be compared. All groups are fed roughage, concentrates, and equal quantities of Indian corn and Kaffir corn during the preliminary period. At the beginning of the test period, Group A receives Kaffir corn in place of Indian corn and Group B Indian corn in place of Kaffir corn. Group C receives the same ration as before, containing equal parts Kaffir corn and Indian corn. Including the transition period, the feeding test lasts 1 to 2 months, and every 8 to 10 days, as before, the average milk production is determined. In the last 10 days of the period the composition of the milk is also determined. An after period of 1 to 2 months follows, in which the food is the same as in the preliminary feeding period. The live weight is also to be determined on three successive days at the end of each period and in each sub-period. All factors except the feed tested should remain constant.

Effect of Nutrition on Milk Production.—The composition and quantity of milk depends; first, upon the capability of the animal and the state of lactation; and secondly, upon the food. The animal cannot increase the milk flow above the limits of the capacity of the animal. An excess of feed will go into body fat. A deficiency of food will decrease the milk flow, shorten the period of lactation, and may permanently injure the productiveness of the animal. The food should be adjusted to the greatest quantity of milk possible to be produced and should be decreased gradually during the period of lactation. When the ration is reduced from a sufficient to an insufficient one, the milk glands do not respond immediately to the change, but they consume more or less body substance for the production of milk, and the condition of the animal becomes visibly worse. This fact is observed so often with cows fresh in milk, that many believe that cows must always become thinner after calving. But the effect of insufficient food soon shows in a decrease in the quantity of milk

and the percentage of fat and dry matter. For example, Fleischer[1] secured the following results:

	Total milk produced per day	Calculated[2] production	Decrease
	kilograms	kilograms	kilograms
Period 1, sufficient food	13.35	—	—
Period 2, insufficient food	9.05	12.70	3.65
Period 3, insufficient food plus oil	8.85	12.05	3.20
Period 4, insufficient food plus bean meal	9.15	11.50	2.35
Period 5, sufficient food	10.10	10.35	—

There was also a falling off in condition of the animal. The insufficient food decreased the milk nearly 30 per cent.

Insufficient food also decreases the ability of the udder to secrete milk, which decrease may become permanent if an insufficient ration is fed for a long time. The decrease in production naturally occurring in the course of lactation, is accelerated by insufficient food, and diminished by abundant food.

If we start with a very insufficient ration, and increase it, the production of milk will increase at first in proportion to the additions, and then the increase in milk will be less for each equal increment of food, until no effect at all is secured. After a certain amount of milk is produced, every increase of production requires a much larger amount of food, increasing quantities of which are stored as body fat. The highest milk production is associated with an improvement in condition.

The greater the productiveness of the animal, the greater is the response to liberal feeding. For example, Kuhn[3] determined the effect of equal additions to the ration of cows having different productiveness, to be as follows:

[1] Jour. f. Landw., 1871, p. 371; 1872, p. 395.

[2] Periods of different length.

[3] Jour. f. Landw., 1876, p. 190.

	Cow No. 1	Cow No. 2
	kilograms	kilograms
Milk production with basal ration	11.77	7.45
Increase caused by addition of 1.5 kg. bean meal	0.92	0.53
Increase caused by addition of 3.0 kg. bean meal	2.40	1.01

The same quantity of bean meal produced twice as much increase in milk with cow No. 1 as with cow No. 2.

Effect of Proteids.—The effect of protein upon milk flow is studied by replacing feeds poor in proteids by those richer in proteids. For example, Fjard and Früs[1] replaced barely meal, which is poor in proteids, by oil cake rich in proteids, in a number of experiments on 8 farms and 1,152 cows, with the following average results:

	Group A	Group B	Group C
Crude protein fed per day	1.08	1.23	1.38
Yield of milk	10.85 kg.	11.45 kg.	11.70 kg.

Increase of proteids thus increased the quantity of milk. It had, however, no effect upon the composition of the milk. From these and other experiments, it is concluded that proteids exert a great influence upon the quantity of milk secreted. The water content of the milk, and the percentage composition of the dry matter are affected only when proteids are fed for a long time in quantities considerably exceeding the needs of the animal. In such event, the water content increases and the fat decreases. Ammonia salts can apparently be used for production of milk when fed in a ration poor in nitrogen but rich in carbohydrates.

Nitrogen-Free Nutrients.—Since fat and carbohydrates may promote flesh production indirectly or pass into body fat, it is evident that they may influence the milk glands and milk production. If the ration contains enough proteid but not enough carbohydrates or fat to induce the highest production, the milk production would not reach its highest limits, but a part of the

[1] Jahresber, f. Agr. Chem., 1893, p. 394.

protein must replace fat or carbohydrates. The addition of carbohydrates or fat should, in such case, increase production. If there is sufficient proteids and the nitrogen-free nutrients are increased, the result depends upon the nutrition of the animal and the capacity of the milk glands, and also upon the depression in digestion of proteids caused by the additions. If the latter occurs to a great extent, a decided depression in milk yield will take place, while with more proteids in the ration, a less decided effect will be produced. With poorly nourished but productive animals, the additions would cause an increase in milk due to better nutrition, which would not appear in the case of a better nourished or a less productive animal. The result of the addition would therefore be different according to conditions, and experiments may give contradictory results.

Both carbohydrates and fat of the feed take part in the production of milk fat. For example, from an experiment of W. H. Jordon,[1] we can calculate the maximum quantity of fat possible to be formed from the fat fed and the proteids fed, and we know from analyses the quantity of fat in the milk:

	Experiment 1	Experiment 2
	kilograms	kilograms
Fat fed in feed	1.5	2.2
Fat possible from proteids	7.8	17.8
Total	9.3	20.0
Fat found in milk	17.6	37.7
Excess, which must have been made from carbohydrates, etc	8.3	17.7

The increase of live weight showed that the animal did not lose weight. After allowing for all the fat possible from protein and fat in the food, there still remains a considerable amount of fat which could only come from carbohydrates.

Increase of carbohydrates does not affect the fat in milk. Ex-

[1] Bulletin 197, New York Geneva Station.

periments to ascertain the effect of an increase in fat in the food on the quantity of fat in the milk, have given contradictory results; but the weight of the evidence is to the effect that the percentage of fat in the milk is not modified by the quantity of fat in the food.

It was observed in Holland that butter from cows on pasture in the fall decreased in volatile acids. Sjollema found that beet heads would prevent this, and later found cane sugar to have the same effect. The pasturage was found to contain less carbohydrates in the fall. It is possible that a part of the volatile acids in butter originate from the fermentation in the animal, and for this reason, a smaller amount was present as the easily fermentable carbohydrates in the food decreased. The character of the fat fed also has an effect upon the composition of the butter. Various experiments in adding oils to rations have produced butter that was somewhat affected by the character of the oil fed.

Harrington[1] found that feeding cottonseed meal made the butter much harder, and decreased the quantity of volatile acids in it. For example, while normal butter contains approximately 7.0 per cent. fatty acids volatile with steam, butter made from the milk of cows fed cottonseed contained in one case only 3.5 per cent. volatile acids.

Standards for Milk Cows.—The amount of feed to be fed must depend upon the quantity of milk given as well as on the weight of the cow. The feeds should be adjusted to the individual animals, and not to the average of the herd. The adjustment may easily be made by arranging the cows in groups according to yield of milk, and adjusting the ration by measuring different quantities of the concentrates for each group. The value of the milk as related to the cost of the feed must determine whether the milk production should be forced to a maximum by giving a heavy ration, or whether a somewhat lower ration should be fed for more economical production. As stated before, the production of the largest possible amount of milk requires much more food than the production of a somewhat smaller amount, as the effect of each addition of food on production diminishes as the

[1] Texas Bulletin, 11.

quantity of feed is increased, and becomes very small near the upper limits of the capacity of the animal.

For the production of one pound of milk, an animal requires about 0.05-0.065 pounds proteids, and 0.05-0.07 pounds productive value, in addition to maintenance requirements. Milk contains 0.18 per cent. lime and 0.15 per cent. phosphoric acid. Only about one-third of the lime and phosphoric acid is digested, so that 10 pounds of milk would require about 25 grams each of lime and phosphoric acid. To this must be added the maintenance requirements of 45 grams of lime and 22 grams of phosphoric acid per 1,000 pounds. The requirements for phosphoric acid are generally met by the food, especially when meadow hay, clovers, or good green fodders are used, but the requirements for mineral matter must not be entirely left out of consideration. Precipitated phosphate of lime may be used if the ration is deficient in lime and phosphoric acid. If deficient in lime alone, precipitated chalk will supply the deficiency.

The following are the amounts of nutrients desirable per day and 1,000 pounds live weight for milk cows:

Yield	Total weight	Proteids	Productive value	Nutritive ratio	Lime grams	Phosphoric acid grams
Ten pounds milk.....	22-27	1.3	2.1	1 : 6.8	70	47
Twenty pounds milk ..	25-29	2.0	2.7	1 : 6.8	95	72
Thirty pounds milk ...	27-33	2.8	3.5	1 : 6.5	120	97
Forty pounds milk	27-34	3.7	4.2	1 : 6.5	145	122
For maintenance only .	15-21	0.7	1.5	1 : 10	—	—
For each 10 lbs. milk ..	—	0.55	0.6	—	—	—

The figures given above for the productive value are for production at the maximum capacity of the animal. For a slightly smaller production, the productive value may be reduced 5 to 10 per cent. The Wisconsin Experiment Station[1] recommends as a good working rule, to feed as many pounds of concentrates (grain feeds) each day, as the cow produces pounds of butter fat per week, in addition to as much roughage as she will eat up clean.

[1] Bulletin No. 200; Research Bulletin No. 13.

CHAPTER XXIV.

FEEDING STANDARDS AND FEEDING.

Feeding standards, as have previously been given, are placed in the form of tables showing the quantity of the different nutrients which should be fed to animals of the various kinds.

Basis of the Standards.—The standards are based, first, upon exact experiments to ascertain the needs of animals, such as described in the preceding pages; secondly, on feeding experiments with various rations, carried on in large number and in various parts of the world, in which the effects of the rations were determined; thirdly, on the experience of practical feeders of large numbers of animals.

What the Standards Represent.—The standards represent the rations which should, as a rule, give the best results. The individuality of the animal will be considered by the wise feeder, and the ration adapted as may be necessary. The standards must in no case be regarded as iron-clad rules, but are merely intended to enable a feeder to start with a well-based, average ration. He should then modify or adapt the ration to suit the requirements of his animals.

Suitability of Feed.—Suitability of the feed must be considered. Some animals are able to take only small quantities of a particular feeding-stuff, or none at all. The palatibility of the food is also to be considered. A mixture of a number of foods diminishes danger from any suspicious food, and distributes the work of digestion over the different digestive organs. Every change in food should be gradual, covering a period of 4 to 7 days, even when the change consists only in a change in quantity.

The Nutritive Ratio.—The nutritive ratio is the ratio of digestible protein to digestible non-protein. We add together the digestible crude fiber, the digestible nitrogen-free extract, and the digestible ether extract multiplied by 2.25, and divide the sum by the digestible protein. The following is an example:

Digestible Nitrogen-free extract	9.6
Digestible crude fiber	14.7
Digestible ether extract 22.4 × 2.25	50.4
Total	74.7
Digestible protein	14.4
Nutritive ratio	1 : 5.2

The nutritive ratio is to be taken chiefly as an aid in calculating the ration. The productive value of the ration, and its content of proteids, are the important factors to be considered. The nutritive ratio should not exceed 1 : 10 for ruminants or 1 : 12 for hogs, but rations containing more protein can be used, if desired. Protein is usually the expensive portion of a ration, but there are localities in which feeds rich in protein are as cheap as other concentrates, or cheaper. Such feeds may then be used in moderate quantity for fattening or other productive purposes. The nutritive ratio is given in the table mainly to aid in calculating the ration which contains a desired productive value associated with a certain quantity of protein. With some feeds it may be that the quantity of protein so calculated may exceed the requirements of the standards, but if so, adjustment may be made by the methods to be pointed out.

Proteids.—The amides and amido compounds have little value for the production or repair of flesh. They may aid in the digestion of food when there is a large quantity of non-protein compared with the quantity of protein present, but otherwise they apparently have little value. Hence it is better to base the ration on its *proteid* content, and not on the protein. The standards which we have given are based upon *digestible proteids* and not on protein.

Fat.—The quantity of fat is not material, provided that it does not exceed one pound per thousand live weight of the animal. If it exceeds this limit, it may derange the digestion of the animal.

Ash.—As a rule the food contains a sufficient quantity of ash for the body, but the ash requires consideration in the case of young animals. Young animals require lime and phosphoric

acid for the purpose of forming bones. A deficiency of either of these is liable to cause injury, or disease. In certain localities, the food is deficient in ash. Deficiency in lime alone is corrected by the use of precipitated chalk; in phosphoric acid, by the use of precipitated or ground phosphate of lime.

Exact Calculation of a Ration.—Before beginning to calculate a ration, it is necessary to decide on the ration desired, the feeds available, and their probable composition. In calculating the ration we must consider:

(1) The desired productive value.
(2) The desired bulk.
(3) The desired proteid content.

All these may vary somewhat, especially the bulk and the proteids.

We will term the method of calculation given below, the method of substitution. It is best illustrated by an example. Suppose we desire a ration with a bulk of about 28 pounds, proteids 2.0 pounds, and productive value of 2.8 pounds, and wish to use corn chops, cottonseed meal, and cottonseed hulls, having the composition given in the table at the end of this chapter. As these feeds all contain about ten per cent. water, for which allowance has been made in considering the total bulk to be fed, it is not necessary to calculate to dry matter.

First, let us assume that the 28 pounds fed is entirely cottonseed hulls. This quantity of cottonseed hulls has a productive value of 0.84 pounds, and the value desired is 2.80 pounds, leaving a deficiency of 1.96 pounds. If now we replace cottonseed hulls having a productive value of 0.03 a pound by corn chops, having a productive value of 0.206, for every pound of cottonseed hulls replaced, we gain 0.206-0.03 = 0.176 pounds productive value. Dividing 1.96 by 0.176 we have 11.1 pounds corn chops, which should replace an equal amount of cottonseed hulls.

Cottonseed hulls 17.9 pounds and corn chops 11.1 pounds contain 0.86 pounds proteids, while 2.0 pounds is desired, a deficiency of 1.14 pounds proteids. Since cottonseed meal has

nearly the same productive value as corn chops, it can replace corn chops without materially altering the productive value of the ration. If one pound average cottonseed meal containing 0.352 pounds digestible protein replace one pound corn chops containing 0.065 pounds digestible protein, the digestible protein increases 0.352-0.065 = 0.287 pounds, so that to increase the ration 1.14 pounds, we require 1.14 divided by 0.287 = 4.0 pounds cottonseed meal in place of an equal quantity of corn chops. The ration would then consist of 17.9 pounds cottonseed hulls, 7.1 pounds corn chops, and 4 pounds cottonseed meal. The substitution of 1 pound cottonseed meal for 1 pound corn chops decreases the productive value 0.206-0.195 = 0.01, or 0.04 pounds for the 4 pounds substituted; and this can be adjusted by adding 0.25 pounds corn chops, making a total of 7.35 pounds corn chops in the ration. This finally gives the ration desired.

The method of calculation here given is as follows:

(1) Assume the bulk desired is composed of the roughage to be used and calculate its productive value.

(2) Calculate the quantity of concentrate which would give the desired productive value if it replaced a portion of the roughage.

(3) Calculate the proteids in the mixture having the composition ascertained above, and then calculate the quantity of a concentrate, rich in proteids, which must replace a portion of the other concentrate in order to give the desired quantity of proteids. The calculation is easier if the two concentrates have nearly the same productive value.

(4) Adjust the ration by increasing or decreasing the quantity of one of the concentrates slightly, so that the change in the productive value caused by the second concentrate may be allowed for.

Improving a Ration.—Suppose a horse weighing 1,000 pounds at hard work, plowing for example, is receiving 7 pounds corn, 6 pounds wheat bran, and 12 pounds timothy hay. How does this ration compare with the standard and how can it be improved?

First, calculate the digestible proteids and productive value of the ration.

	Digestible proteids		Productive value
Corn	$7 \times 0.068 = 0.48$		$7 \times 0.206 = 1.44$
Wheat bran	$6 \times 0.12 = 0.72$		$6 \times 0.12 = 0.72$
Timothy hay	$12 \times 0.021 = 0.25$		$12 \times 0.078 = 0.94$
Total	25	1.45	3.10
Standard	23–28	2.0	3.8

The ration is too low in proteids and in productive value. Productive value may be increased by substituting corn for timothy hay. One pound corn substituted increases the productive value 0.206-0.078 = 0.128; so to gain the 0.7 pound desired would take 5.5 pounds corn chops. Each pound of corn chops substituted would increase the proteids in the ration 0.068-0.021 = 0.047 pounds, or 5.5 pounds would increase it 0.26 pound. This would increase the total proteids to 1.71, but would still leave a deficiency of 0.29 pounds proteids. If we replace corn by cottonseed meal to supply this protein, we require $0.29 \div (0.352\text{-}0.068) = 1.0$ pound cottonseed meal.

The calculated ration would then be as follows:

		Pounds
Corn	$7 + 5.5 - 1.0 =$	11.5
Wheat bran	$=$	6.0
Timothy hay	$12 - 5.5 =$	6.5
Cottonseed meal	$=$	1.0
Total		25.0

Reducing the Cost of a Ration.—The commercial prices of feeding-stuffs are often not in proportion to their feeding values, and rations may often be modified so as to reduce the cost of the ration. There are four things to be considered in reducing the cost of a ration: (1) the suitability of the feed to the animal; (2) the cost of the productive value; (3) the cost of the digestible proteids per pound; (4) the cost of the bulk or volume of the feed.

The three last factors can be calculated from the known selling price, and the proteid content and productive value of the feeds. The bulk of the feed is of course measured by the total amount of dry matter. It often happens that hays cost more per unit of feeding value than concentrated feeds. In such cases, the cheaper bulky feeds should be used, and the difference in nutritive value compensated for by increasing the concentrates. The following table shows the relative cost of nutrients on the Texas market in 1910-11:

RELATIVE COST OF NUTRIENTS.

	Selling price per ton	Cost of one pound digestible protein	Cost of one pound productive value
		Cents	Cents
Cotton seed meal	$28.00	3.6	7.3
Wheat shorts	28.00	10.7	7.9
Wheat bran	27.00	10.8	11.2
Corn chops	27.00	20.7	6.5
Kaffir corn chops	25.00	17.8	6.8
Milo maize chops	25.00	17.8	6.8
Rice polish	24.00	14.4	5.7
Rice bran	18.00	10.0	4.5
Cotton seed	23.50	8.1	5.5
Cotton seed hulls	8.50	70.8	14.1
Alfalfa hay	18.50	12.3	11.7

Suppose a feeder who is using 6 pounds wheat bran at a cost of $30.00 a ton, can secure corn at $30.00 and cottonseed meal at $40.00. Would it pay to substitute? Six pounds wheat bran contains 0.72 pounds proteids and 0.72 pounds productive value. Three and one-half pounds corn would contain 0.72 pounds productive value and 0.241 pounds proteids, or a deficiency of 0.48 pounds proteids. Replacing corn by cottonseed meal, $0.48 \div 0.352 - 0.068 = 1.4$ pounds. That is, 1.4 pounds cottonseed meal and 3.5 pounds corn are equivalent to 6 pounds wheat bran. The cost would be $6 \times 1.5 = 9$ cents for wheat bran; and for the mixture, $1.4 \times 2.0 = 2.8$ cents for the cottonseed meal, and for the corn $3.5 \times 1.5 = 5.25$ cents, a total of 8.05 cents for the mixture or a difference of 0.95 cents, nearly one-ninth in favor of

the mixture. The difference in bulk of the ration should be adjusted when such substitutions are made, unless it comes within the range of the variations allowed.

The preceding illustration shows the method which may be followed in reducing the cost of a ration. In substituting for proteids, a suitable feed providing the proteids at the lowest cost per unit should be used. In substituting for productive value a suitable feed providing the most productive value for the money should be used, and the same remark applies to substituting for bulk.

Tables of Feeding Value.—The following tables show the feeding values of a number of feeds.

AVERAGE FEEDING VALUE OF FEEDS.

	Total dry matter in 100 lbs.	Digestible proteids in 100 lbs.	Productive value in 100 lbs.
GRAIN AND SEED			
Barley	89.1	8.4	18.8
Corn	89.1	6.8	20.6
Corn and cob meal	84.9	4.5	16.5
Kaffir corn	89.9	7.0	18.3
Oats	89.0	8.0	15 0
Pea meal	89.5	16.8	16.6
Milo maize	89.5	7 1	18.4
Rye	88.4	8.1	18.9
Wheat	89.5	8.9	17.3
Cotton seed	89.7	14.5	21.2
BY-PRODUCTS			
Brewers grains, dry	92.0	19.0	14.0
Cottonseed meal, average	91.8	35.2	19.5
Cottonseed meal, Texas	92.0	39.0	19.1
Gluten feed, dry	91.9	20.0	18 4
Linseed meal, old process	90.8	27.5	18.4
Linseed meal, new process	90 1	29.3	17.4
Rye bran	88.2	11.4	13.2
Wheat bran	88.1	12.0	12.0
Wheat shorts	87.9	13.0	17.6
Rice bran	90.1	9.0	19.8
Rice polish	88.5	8.3	20.9
Corn bran	90.9	6.5	18.6
Peanut meal	89.3	42.9	20.2
Cold pressed cottonseed cake	90.2	17.1	10.0
Molasses (cane)	77.6	—	13.2
Corn cobs	89.3	0.7	5.3
Oat hulls	92.7	0.3	4.5
Rice hulls	91.0	0.4	0.7
Wheat chaff	85.7	0.9	6.1
Cottonseed hulls	88.9	0.6	3.0

AVERAGE FEEDING VALUE OF FEEDS.—(*Continued.*)

	Total dry matter in 100 lbs.	Digestible proteids in 100 lbs.	Productive value in 100 lbs.
GREEN FODDER AND SILAGE			
Alfalfa	28.2	2.5	2.9
Red clover	29.2	2.2	3.8
Crimson clover	19.1	2.2	2.6
Corn fodder	20.7	0.4	2.9
Corn silage	25.6	1.2	3.9
Rape	14.3	2.2	2.6
HAY AND COARSE FODDER			
Alfalfa	91.6	6 9	7.9
Clover hay	84.7	5.4	8.1
Corn forage	57.8	2.1	7.1
Cowpea hay	89.3	8.6	10.0
Oat hay	84.0	2.6	8.6
Timothy hay	86.8	2.1	7.8
Oat straw	90.8	1.1	4.9
Rye straw	92.9	0.6	4.9
Wheat straw	90 4	0.4	3.9
Rice straw	88.0	1.0	3.4
Corn shucks	87.2	1.0	8.2
ROOTS AND TUBERS			
Carrots	11.4	0.4	1.8
Mangel wurzels	9.1	0.1	1.1
Potatoes	21.1	0.5	4.2
Rutabagas	1.4	0.9	1.8
Turnips	9.4	0.2	1.3

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